SIMULATED EFFECTS OF GROUND-WATER PUMPAGE ON STREAM–AQUIFER FLOW IN THE VICINITY OF FEDERALLY PROTECTED SPECIES OF FRESHWATER MUSSELS IN THE LOWER APALACHICOLA–CHATTAHOOCHEE–FLINT RIVER BASIN (SUBAREA 4), SOUTHEASTERN ALABAMA, NORTHWESTERN FLORIDA, AND SOUTHWESTERN GEORGIA

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Well-Naming System

Wells used in this report are named according to a system based on the USGS index of topographic maps. Each 7.5-minute topographic quadrangle in Georgia has been given a number and letter designation beginning at the southwestern corner of the State. Numbers increase eastward and letters increase alphabetically northward. Quadrangles in the northern part of the area are designated by double letters. The letters “I,” “II,” “O,” and “OO” are omitted. Wells inventoried in each quadrangle are numbered consecutively beginning with 1. Thus, the 520th well numbered on the 09E quadrangle is designated 09E520.

Station-Identification Numbers

The system used by the U.S. Geological Survey to assign identification numbers for surface-water stations and for ground water well sites differ, but both are based on geographic location. Since October 1, 1950, the order of listing hydrologic-station records in USGS reports is in a downstream direction along the main stream. The station-identification number is assigned according to downstream order. The complete number for each station, such as 02356000 includes the two-digit part number “02” plus the downstream-order number “356000,” which can be from six to 12 digits.

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Simulation results indicate that ground-water withdrawal in the lower Apalachicola-Chattahoochee-Flint River basin during times of drought could reduce stream–aquifer flow and cause specific stream reaches to go dry. Of the 37 reaches that were studied, 8 reaches ranked highly sensitive to pumpage, 13 reaches ranked medium, and 16 reaches ranked low. Of the eight reaches that ranked high, seven contain at least one federally protected mussel species.

Small tributary streams such as Gum, Jones, Muckalee, Spring, and Cooleewahee Creeks would go dry at lower pumping rates than needed to dry up larger streams. Other streams that were ranked high may go dry depending on the amount of upstream flow entering the reach; this condition is indicated for some reaches on Spring Creek. A dry stream condition is of particular concern to water and wildlife managers because adequate streamflow is essential for mussel survival.

INTRODUCTION

Ground-water withdrawal for irrigation in southwest Georgia more than doubled between 1977 and 1981 (Hayes and others, 1983). Along with this increase in irrigation came an increase in concern over possible effects of further ground-water development on the water resources and biota of the lower Apalachicola–Chattahoochee–Flint (ACF) River basin (fig. 1). Of particular concern to water and wildlife managers is the potential for pumpage to cause unacceptable declines in water levels in wells and in discharge to streams. This concern led Federal, State, and local officials to conduct several studies with the U.S. Geological Survey (USGS) during the 1980's and 1990's to investigate the effects of increased ground-water development on the hydrologic system. These studies indicated a strong connection between pumpage and reduced streamflow in southwest Georgia (Hayes and others, 1983; Torak and others, 1996; Torak and McDowell, 1996).

An associated concern of State and Federal officials is the effect of pumpage in the lower ACF River basin on streamflow in reaches containing federally protected freshwater mussel populations. The most commonly cited cause of mussel extinction is habitat degradation (Havlik, 1981; Layzer and others, 1993). Adequate streamflow is the hydraulic characteristic necessary to maintain mussel habitat (Richard J. Neves, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Polytechnic Institute and State University, oral commun., 2001). Because of limited mobility (Layzer and Madison, 1995), short-term but often substantial fluctuations in streamflow can change hydraulic conditions faster than mussels can move, thus limiting the chance of survival under extreme low-flow conditions. Torak and McDowell (1996) indicated that simulated pumpage-induced changes in streamflow could cause some stream reaches to go dry. In addition to direct impacts on mussels, reduced streamflow could result in elimination of host fish populations, unsuccessful freshwater mussel fertilization, and failed attempts of glochidia to attach to host fish (U.S. and Wildlife Service, 1998).

Currently (2001), the U.S. Fish and Wildlife Service (USFWS) protects seven species of freshwater mussels in the Apalachicola Region (U.S. Fish and Wildlife Service, 1998). Five species have been declared endangered and two species have been identified as threatened under the Endangered Species Act of 1973, as amended on March 16, 1998, due to significant reductions in the populations of these species (Brim Box and Williams, 2000) by habitat loss and alteration (Butler and Alam, 1999). The five endangered species are the fat threeridge (*Amblema neislerii*), shinyrayed pocketbook (*Lampsilis subangulata*), Gulf moccasinshell (*Medionidus penicillatus*), Ochlockonee moccasinshell (*Medionidus simpsonianus*), and oval pigtoe (*Pleurobema pyriforme*). The two threatened species are the Chipola slabshell (*Elliptio chipolaensis*) and purple bankclimber (*Elliptio sloatianus*). All these species—except for the Ochlockonee moccasinshell—reside in the lower ACF River basin.

In August 1999, the USGS began a cooperative investigation with the USFWS to study the effect of ground-water pumpage on stream–aquifer flow in stream reaches containing federally protected mussel species in the lower ACF River basin. Stream reach sensitivity to changes in pumpage, stream stage, and ground-water level is of concern to the USFWS because the potential exists for stream reaches containing federally protected mussel species to go dry, thus eliminating mussel habitat under natural and anthropogenic hydrologic stresses.

Purpose and Scope

This report describes the simulated effects of pumpage, climatic conditions, and hydrologic boundaries on stream–aquifer flow between the Upper Floridan aquifer and streams containing populations of federally protected mussel species in the lower ACF River basin. Stream–aquifer flow is the flow of water across the streambed between the aquifer and the stream that either increases or decreases streamflow. This project combined results from a previous USGS investigation (Torak and McDowell, 1996) with two sources of mussel-survey information (Brim Box and Williams, 2000; Paula M. Johnson, Jones Ecological Research Center, written commun., 1999). Changes in simulated stream–aquifer–flow rates determined by Torak and McDowell (1996) were used to rank stream reaches according to their sensitivity to hydrologic stress. Results were compared with known locations of federally protected mussel species identified from previous studies to assess possible effects of pumpage on mussel habitat.

Results presented herein are not intended to predict a pumping scenario or boundary condition under which a specific stream reach will go dry, although this information can be inferred from the illustrations; rather, the intent of this report is to indicate which stream reaches are more sensitive to imposed hydrologic stress than others, based on previous simulations. This information will assist the USFWS in managing current and future mussel populations.

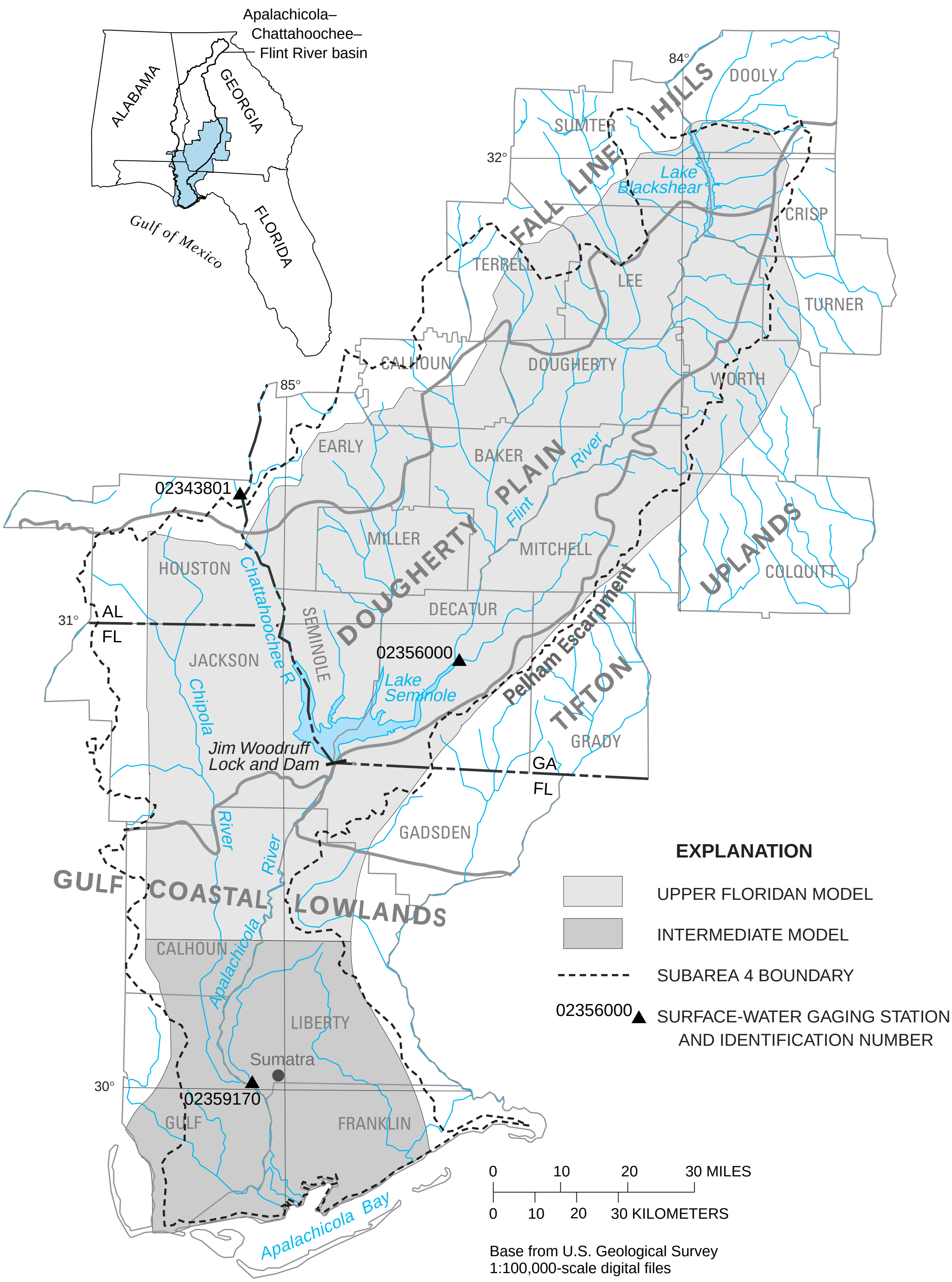


Figure 1. Study area, model boundary, and physiographic districts in the lower Apalachicola–Chattahoochee–Flint River basin.

Method of Study

Results of digital modeling from Torak and McDowell (1996) were utilized in this study to describe the effects of pumpage on stream–aquifer flow within the lower ACF River basin. These results were plotted and information on the graphs was used to quantitatively rank stream reaches according to their response to simulated pumpage and hydrologic boundary conditions. Locations of federally protected freshwater mussels determined from previous studies were superimposed on a map depicting ranked reaches to identify which mussel species may be threatened or in danger of becoming extinct because of their location in a highly sensitive stream reach.

Stream-reach response to pumpage was simulated under six different hydrologic scenarios. Two conditions of aquifer and overburden head conditions (normal and dry), and three conditions of stream stage (October 1986, Q_{50}, Q_{90}) were used along with multiples of October 1986 pumping rates (*n*, *n* = 0.5, 1, 2, and 5) to evaluate the effect of pumpage and climate on stream–aquifer flow. Normal head conditions are long-term average ground-water levels over the period of record and refer to water levels used at model boundaries and in the overburden during simulation. Dry head conditions are water levels used at model boundaries and in the overburden in simulations representing dry (October 1986) conditions. Dry stream conditions were simulated using drought (October 1986) stream-stage conditions. Flow condition Q_{50} is the stage corresponding to discharge that is exceeded 50 percent of the time over the period of record (median flow), and Q_{90} is the stage associated with flow that is exceeded 90 percent of the time over the period of record (low flow). For some streams, surface-water records indicated that streamflow for October 1986 represented a flow that was lower than Q_{98} (Torak and McDowell, 1996). Each scenario combined one head condition with one streamflow (stage) condition. Four simulations were conducted for each scenario: each scenario used four different pumpage multipliers of October 1986 rates. Simulated stream–aquifer flow for each reach was plotted and the data used to rank each reach. Maps showing ranked stream reaches were combined with maps depicting locations of federally protected mussels.

Description of the Study Area

The study area is located in the lower ACF River basin, a 6,800 square-mile (mi^2) area including parts of southeastern Alabama, northwestern Florida, and southwestern Georgia (fig. 1). The area defined by the ACF and Alabama–Coosa–Tallapoosa (ACT) River basins was subdivided into eight subareas by the U.S. Army Corps of Engineers for a comprehensive study that began in January 1992 under a Memorandum of Agreement among the States of Alabama, Florida, and Georgia; and the U.S. Department of the Army. The lower ACF River basin was identified as Subarea 4. The northern boundary of Subarea 4 (fig. 1) approximates the updip limit of the karstic Upper Floridan aquifer, which strikes in a northeast direction from southeastern Alabama to south-central Georgia. The eastern boundary extends south and southwest along a surface-water divide called the Pelham Escarpment (Hayes and others, 1983)—also called the Solution Escarpment by MacNeil (1947)—into Florida. In Florida, the eastern boundary runs along a surface-water divide to the Gulf of Mexico. The southern boundary is the coastline along the Gulf of Mexico and forms a ground-water outflow boundary. A surface-water divide west of the Apalachicola and Chipola Rivers forms the western boundary of the study area.

Physiography

Subarea 4 is part of a larger region called the Coastal Plain physiographic province (Fenneman, 1938), an area in the southeastern, eastern, and northeastern United States where surface geology consists of formations of Cretaceous or younger strata sloping gently and thickening towards the sea. Within the study area, the Coastal Plain physiographic province is further subdivided into physiographic subdivisions, called districts, based upon similar geologic and geomorphologic characteristics (fig. 1).

Clark and Zisa (1976) described the Georgia region of Subarea 4 as three different districts: the Fall Line Hills, Dougherty Plain, and Tifton Uplands (fig. 1). In the Florida panhandle portion of the study area, there are three physiographic districts: the Dougherty Plain, the Tifton Uplands, and the Gulf Coastal Lowlands (Arthur and Rupert, 1989). For further descriptions of these districts, the reader is referred to Puri and Vernon (1964), Middleton (1968), White (1970), Sapp and Emplaincourt (1975), Brooks (1981), Hayes and others (1983), Wagner and Allen (1984), and Hicks and others (1995).

River and Lake System

Four principal rivers drain the study area—the Chattahoochee, Flint, Apalachicola, and Chipola (fig. 1). The Chattahoochee River drains approximately 1,800 mi^2 of Coastal Plain sediments in Alabama and Georgia, enters the study area near Dothan, Ala., flows 50 mi south to Lake

Seminole, and mixes with the Flint River. Few tributaries flow into the Chattahoochee River in Subarea 4. In this reach, the Chattahoochee River has cut into the limestone, and contours of the potentiometric surface intersect the river at acute angles pointing upstream, indicating a strong hydraulic gradient from the aquifer to the river (Torak and McDowell, 1996). Long-term median flow for the Chattahoochee River near Columbia, Ala. (USGS gaging station 02343801, fig. 1), is about 14,500 cubic feet per second (ft^3/s). Long-term minimum flow is about 1,350 ft^3/s, and long-term maximum flow is about 59,500 ft^3/s.

The Flint River enters the northern part of the study area north of Lake Blackshear, and flows south-southwest along the base of the Pelham Escarpment to Lake Seminole, draining approximately 6,000 mi^2 of the Coastal Plain. Long-term median streamflow as of April 2001, for the Flint River at Bainbridge, Georgia (USGS gaging station 02356000, fig. 1), is about 11,900 ft^3/s. The long-term minimum and maximum flows are about 4,660 and 50,310 ft^3/s, respectively. Numerous major and minor streams flow into the Flint River along its extent in Subarea 4. Most streams contributing flow to the Flint River originate to the northwest. The streams on the western side of the Flint River are longer and contribute more flow to the Flint River than streams on the east side. Most streams located east of the Flint River in the Dougherty Plain originate on the Pelham Escarpment. The Pelham Escarpment serves not only as a major surface-water divide but also as a ground-water divide between the Dougherty Plain and the Tifton Uplands.

Lake Seminole is a 37,600-acre lake created in 1957 by the U.S. Army Corps of Engineers by the construction of the Jim Woodruff Lock and Dam across the Apalachicola River (fig. 1). The lake is located at the confluence of the Chattahoochee and Flint Rivers. Construction of the dam began in 1950, and subsequent filling of the reservoir occurred from 1954 to 1957. The structure was built for navigational and hydropower purposes and provides about 30 ft of lift from the Apalachicola River to the lake surface, which maintains a normal pool altitude of about 77 ft.

The Apalachicola River begins at the Jim Woodruff Lock and Dam and flows more than 100 mi south into Apalachicola Bay. The Apalachicola River and its major tributary—the Chipola River—drain almost 2,400 mi^2 (Elder and Cairns, 1982). Long-term median streamflow for the Apalachicola River at Sumatra, Fla. (USGS gaging station 02359170, fig. 1), is about 34,600 ft^3/s. Long-term minimum and maximum streamflow for the Apalachicola River at this station is about 12,800 and 87,100 ft^3/s, respectively. The Apalachicola River is a wooded river-wetland system that produces and transports large amounts of detritus to Apalachicola Bay. Annual flushing of organic matter by seasonal high streamflow helps support economically viable offshore populations of blue crab, shrimp, and oysters (Elder and Cairns, 1982).

The Chipola River originates in the southeast corner of Alabama and flows south to the Apalachicola River near Sumatra, Fla. Most tributaries of the Chipola River flow from the west and are longer than tributaries to the east.

Precipitation

Precipitation plays a critical role in recharging both surface and ground waters in Subarea 4. Average annual rainfall is approximately 46 inches per year in Crisp County (northern part of the study area) and increases southwesterly to Apalachicola Bay where it approaches 60 inches per year (Bush and Johnston, 1988). On average, rainfall is greatest during winter and mid-summer (fig. 2).

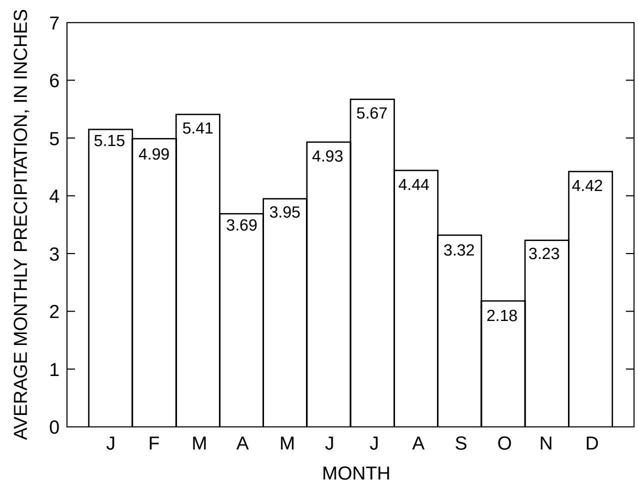


Figure 2. Average monthly precipitation for southwest Georgia, 1899–1998 (National Oceanic and Atmospheric Administration, 1998).

Long-term monthly averages (fig. 2) indicate the study area receives more precipitation in July than in any other month of the year. Precipitation is lowest in October. Stream-stage records for the Flint River at Bainbridge, Ga. (gaging station 02356000, fig. 1), indicate mean-monthly stage is usually highest in February or March and lowest in summer or fall (U.S. Geological Survey, 1981–99). The Upper Floridan aquifer shows a pronounced response to climatic changes in the northwestern part of the study area where the aquifer and depth to water is shallow (Hayes and others, 1983). During September through May, streamflow and ground-water levels respond quickly to precipitation; during June through August, evaporation is high and precipitation has less of an effect. Rainfall during summer tends to be short in duration and high in intensity; rainfall during winter tends to be long in duration and moderately intense. Rainfall-induced changes in ground-water level and streamflow are subdued in the southern part of the study area where the depth to the aquifer is greater than in the north.

Geohydrology

The sequence of geologic units in southeastern Alabama, northwestern Florida, and southwestern Georgia constitutes a series of geohydrologic units having varying hydraulic characteristics that either restrict or transmit the flow of water. In Georgia, the principal source of water supply is the highly permeable, karstic Upper Floridan aquifer, which is confined below by the Lisbon Formation (Torak and others, 1996) and semiconfined above by undifferentiated overburden (fig. 3). In this area, streams are in direct connection with the Upper Floridan aquifer. In the Florida panhandle near the Gulf of Mexico, the Upper Floridan aquifer is hydraulically separated from the Intermediate system by a semiconfining unit (Torak and others, 1996). Streams in this part of the study area are in hydraulic connection with the Intermediate system. Additional details about the geohydrology in this area can be obtained from Torak and others (1996), Torak and McDowell (1996), Hayes and others (1983), Hicks and others (1995), Miller (1986), and Bush and Johnston (1988).

Acknowledgments

The authors extend sincere appreciation to all who have contributed to this report. The authors thank Amy Benson, USGS, Panama City, Fla., for providing coverages of federally protected mussel locations used in Brim Box and Williams (2000). The authors also thank Paula M. Johnson (Jones Ecological Research Center, Newton, Ga.) for survey results in the lower ACF River basin and for suggestions on improving this report. The authors greatly appreciate precipitation data supplied by Fred Haines of International Paper Company near Bainbridge, Ga. Caryl J. Wipperfurth, USGS, Atlanta, Ga., produced the illustrations in this report.

SERIES	GEORGIA GEOLOGIC UNIT	GEORGIA HYDROLOGIC UNIT	FLORIDA GEOLOGIC UNIT	FLORIDA HYDROLOGIC UNIT
HOLOCENE AND PLEISTOCENE	Terrace and undifferentiated deposits	Semiconfining unit	Terrace and undifferentiated deposits	Semiconfining unit
MIOCENE	Undifferentiated overburden (residuum)	Semiconfining unit	Citronelle Formation	Semiconfining unit
MIOCENE	Undifferentiated overburden (residuum): Miccoskee Formation	Semiconfining unit	Jackson Bluff Formation	Semiconfining unit / Intermediate system
MIOCENE	Undifferentiated overburden (residuum): Hawthorn Formation	Semiconfining unit	Alum Bluff Group: Chipola Formation, Hawthorn Formation	Intermediate system
MIOCENE	Undifferentiated overburden (residuum): Hawthorn Formation	Semiconfining unit	Intracoastal Formation	Underlying semiconfining unit
MIOCENE	Undifferentiated overburden (residuum): Tampa Limestone	Upper Floridan aquifer	Tampa Limestone	Underlying semiconfining unit
OLIGOCENE	Undifferentiated overburden (residuum): Suwannee Limestone	Upper Floridan aquifer	Suwannee Limestone	Underlying semiconfining unit / Upper Floridan aquifer
OLIGOCENE	Undifferentiated overburden (residuum): Suwannee Limestone	Upper Floridan aquifer	Marianna Formation	Upper Floridan aquifer
EOCENE	Ocala Limestone; Clinchfield Sand	Upper Floridan aquifer	Ocala Limestone	Upper Floridan aquifer
EOCENE	Lisbon Formation	Lower confining unit	Lisbon Formation	Sub-Floridan confining unit

Figure 3. Correlation chart of geologic and hydrologic units in the lower Apalachicola–Chattahoochee–Flint River basin (modified form Torak and McDowell, 1996).

STREAM–AQUIFER RELATIONS

The connection between ground water and surface water in the study area is well documented. Hicks and others (1995) discussed the relation between ground water and surface water in the Albany, Ga., area. Large solution conduits transport water from the Upper Floridan aquifer to the Flint River. Numerous springs discharge ground water from the Upper Floridan aquifer to streams in the lower ACF River basin. Several modeling studies describe the connection between streams and the Upper Floridan aquifer (fig. 4) in all or parts of the study area and the effect of natural and/or anthropogenic stress on stream–aquifer flow (Hayes and others, 1983; Faye and Mayer, 1990, 1996; Torak and others, 1996; Torak and McDowell, 1996).

Stream–aquifer flow is the flow of water across the streambed that either increases or reduces streamflow (Torak and McDowell, 1996), and is the principal mechanism governing the amount of water at any point along a stream during periods of baseflow. Every point along a stream reach has a set of characteristics that determine the volumetric flow at that point. Stream–aquifer flow is a function of stream dimensions, hydraulic conductivity of streambed materials, streambed thickness, stage of the stream, and head in the aquifer. Of all the factors listed above, stream stage and aquifer head are the most dynamic; these two factors change frequently, if not continuously, to cause changes in stream–aquifer flow.

The connection of ground water with surface water in the study area is further illustrated by equipotential contours on a potentiometric surface map constructed by Peck and others (1999) (fig. 5). Ground-water flow is from high hydraulic head to low hydraulic head in a direction perpendicular to potentiometric contours. Potentiometric contours bend upstream at acute angles indicating a substantial connection between ground water and streams; closely spaced contours indicate a large hydraulic gradient between the aquifer and the stream. Flow is from upland areas to streams.

Precipitation, ground-water levels, and stream stage vary seasonally (fig. 6). Although precipitation is highest during summer months, ground-water levels and streamflow are highest during winter months. These converse responses result from a combination of factors: (1) summer precipitation, while of high intensity is short in duration, resulting in high runoff and low infiltration; (2) evapotranspiration is high in summer, intercepting a percentage of precipitation before it can infiltrate to the ground-water system; and (3) irrigation pumpage during the summer months lowers ground-water levels and reduces ground-water discharge to streams.

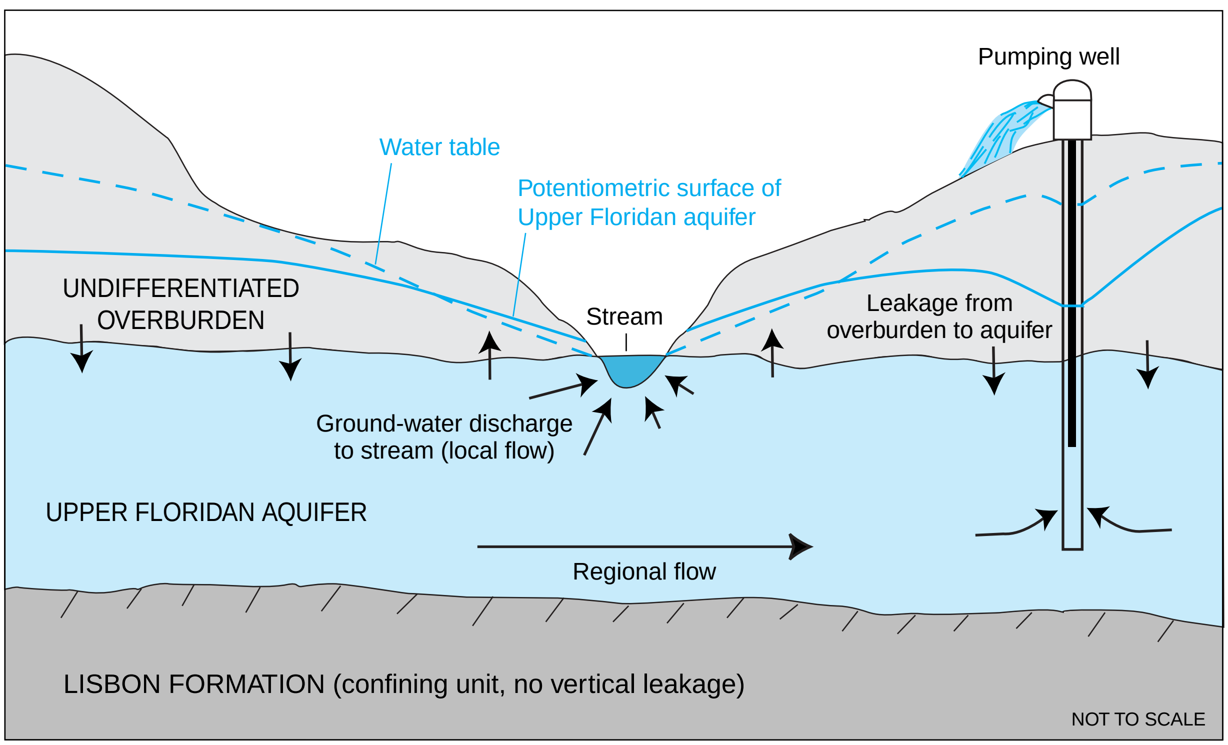


Figure 4. Conceptualization of stream-aquifer flow with a nearby pumping well in the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and others, 1993).

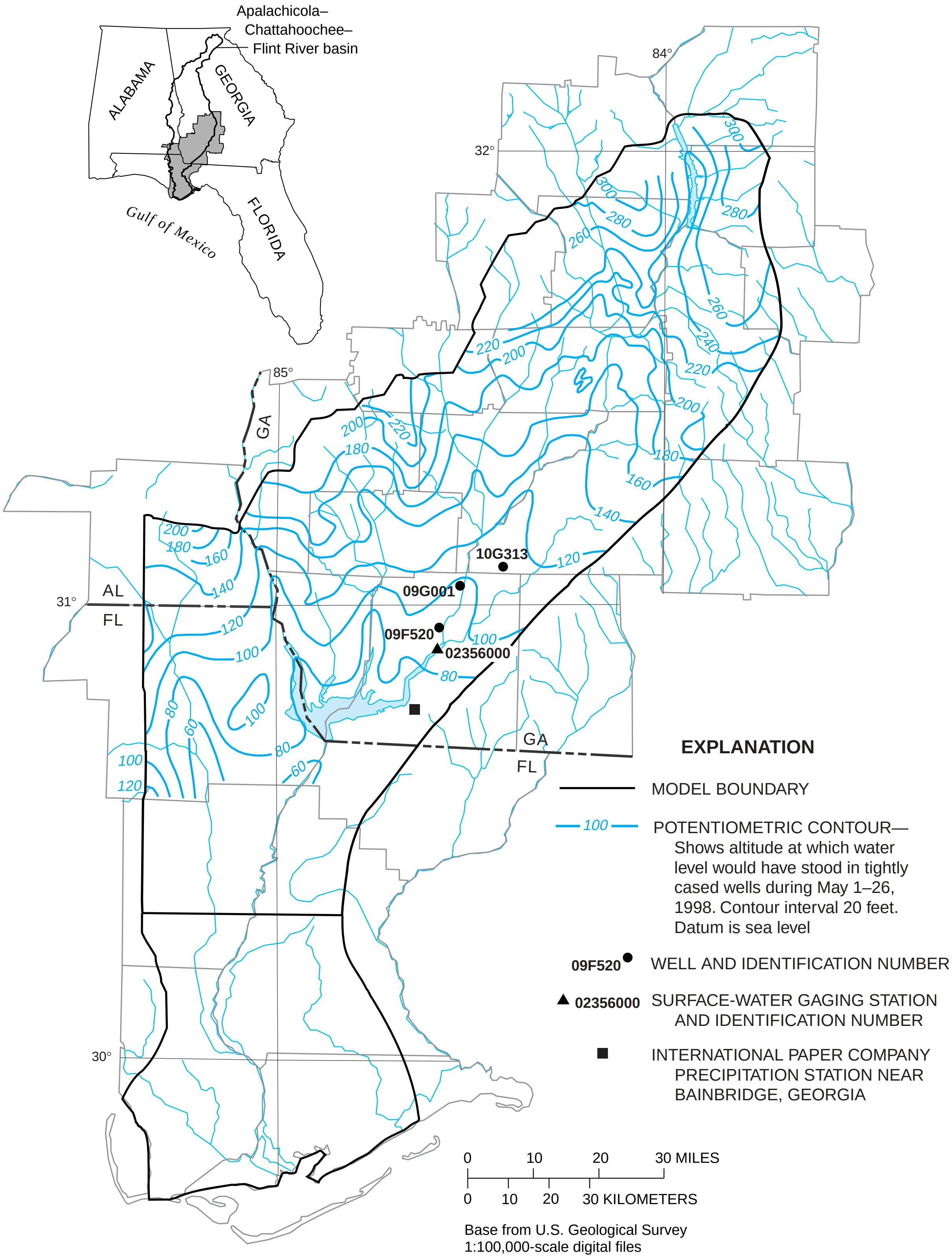


Figure 5. Potentiometric surface of the Upper Floridan aquifer in the lower Apalachicola–Chattahoochee–Flint River basin (modified from Peck and others, 1999), and location of U.S. Geological Survey monitoring wells, gaging station 02356000, and International Paper Company precipitation station near Bainbridge, Georgia.

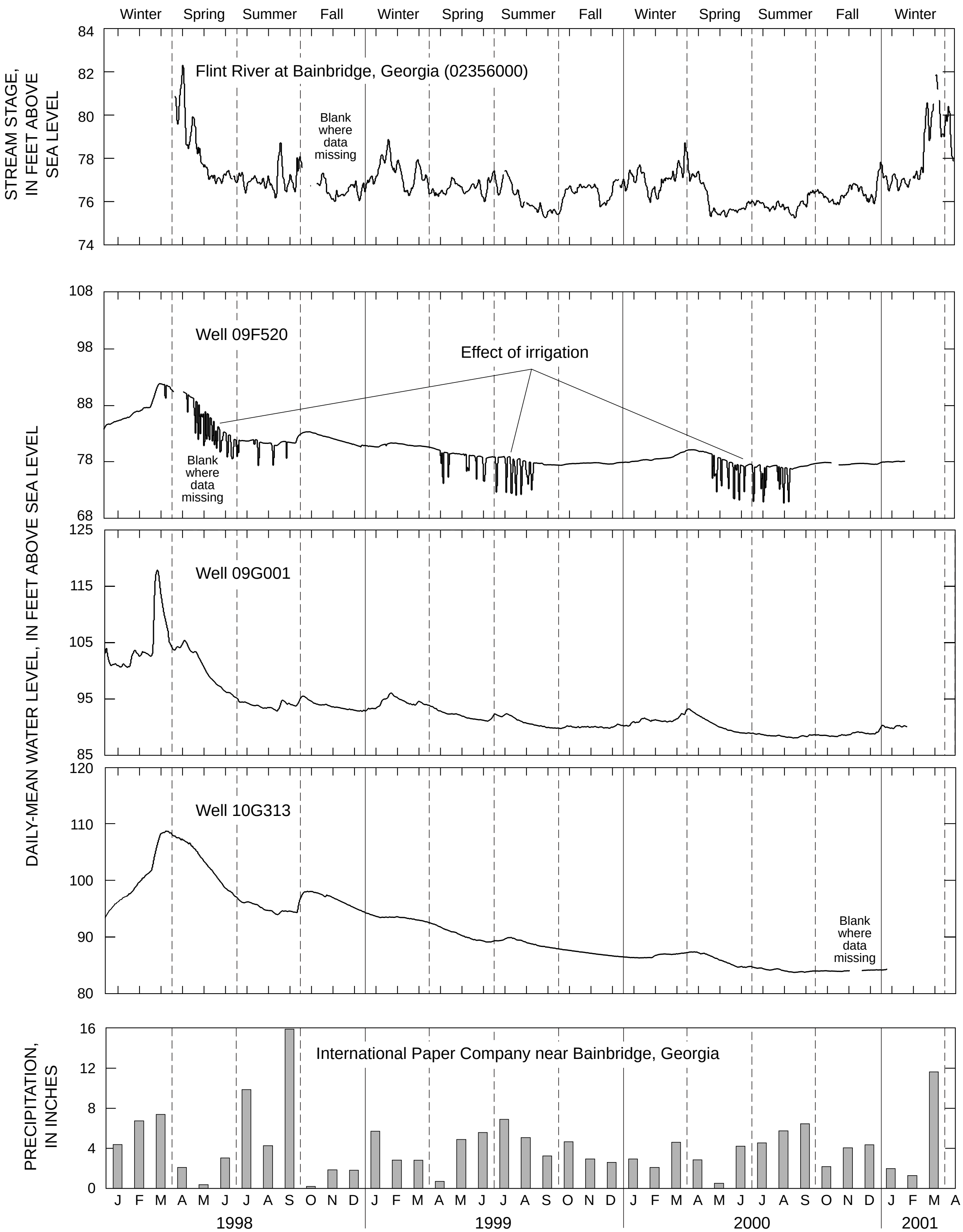


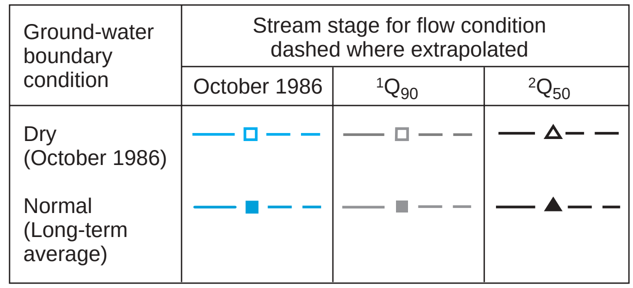
Figure 6. Stream stage for the Flint River at Bainbridge (02356000); water levels at U.S. Geological Survey monitoring wells 09F520, 09G001, and 10G313; and monthly total precipitation near Bainbridge, Georgia (see fig. 5 for location).

SIMULATION OF STREAM–AQUIFER FLOW

Results of steady-state digital models of the Upper Floridan aquifer and Intermediate system, constructed by Torak and others (1996) and Torak and McDowell (1996), were used in this study to assess pumpage-induced changes in stream–aquifer flow in stream reaches containing federally protected mussel species in the lower ACF River basin. The models utilized the USGS Modular Finite-Element model (MODFE) for ground-water flow (Cooley, 1992; Torak, 1993a,b). Simulation results are presented in tables in Appendix A.

In the study by Torak and others (1996), two steady-state models were constructed to show the effect of ground-water pumpage on stream–aquifer flow during a period of drought. One of these two models, termed the Upper Floridan model, simulated ground- and surface-water interaction in the northern and central part of Subarea 4 (fig. 1), where surface-water features are in direct hydraulic connection with the Upper Floridan aquifer. The second model, termed the Intermediate model, simulated ground- and surface-water interaction in the southern part of Subarea 4, where surface-water features are not connected hydraulically with the Upper Floridan aquifer, but rather are connected with the Intermediate aquifer and surficial deposits.

In a second study (Torak and McDowell, 1996), the Upper Floridan and Intermediate models were utilized to show the effect of pumpage, stream stage, and ground-water level on stream–aquifer flow by combining six scenarios of surface-water and ground-water conditions with four multiples (*n*) of the October 1986 pumping rate (n = 0.5, 1, 2, 5). Each scenario (fig. 7) consisted of a ground-water-level condition (“dry” October 1986 conditions or “normal” long-term average conditions), and a stream-stage condition (October 1986, Q_{90}, or Q_{50}). Stream-stage-condition October 1986 refers to the stage associated with measured streamflow in late October 1986. Stream-stage-condition Q_{90} is the stage associated with streamflow that is exceeded 90 percent of the time, and stream-stage-condition Q_{50} is the stage associated with streamflow that is exceeded 50 percent of the time. Simulations results provide computed values of stream–aquifer flow for 37 stream reaches in Subarea 4, based on given conditions of pumpage, ground-water level, and stream stage. Graphical results, by stream reach, are presented in Appendix B. For additional details pertaining to model input, the reader is referred to Torak and others (1996) and Torak and McDowell (1996).



[1] Streamflow equal to or exceeded 90 percent of the time (low-flow condition)
[2] Streamflow equal to or exceeded 50 percent of the time (median streamflow condition)

Figure 7. Matrix showing six different hydrologic scenarios used in the Torak and McDowell (1996) simulations.

Model Representation of Stream Reaches

Torak and others (1996) and Torak and McDowell (1996) divided streams in the lower ACF River basin into 37 stream reaches (fig. 8) based on discharge measurements made in October 1986 at 94 points along streams in the basin (table 1 in Torak and others, 1996). Stream reaches were represented in digital models by using either a linear or nonlinear, head-dependent, Cauchy-type boundary (Torak, 1993a). The linear, head-dependent, Cauchy-type boundary either allows water from the stream to recharge the aquifer or allows ground water from the aquifer to discharge to the stream. This condition assumes the stream would not go dry under losing-stream conditions. The nonlinear, head-dependent, Cauchy-type boundary does not allow water from the stream to recharge the aquifer, as it is assumed that the stream would go dry under losing-stream conditions. Nineteen small stream reaches draining the upland areas of the lower ACF River basin (Upper Floridan model only) were represented with nonlinear, head-dependent, Cauchy-type boundaries, as some of these streams were observed to be dry or nearly dry during October 1986. Also, other streams were represented with the nonlinear boundary if the potential existed for them to go dry during simulation of increased pumpage from October 1986 rates (Torak and others, 1996). Eighteen larger stream reaches that were not dry during October 1986 nor expected to go dry during simulation of pumpage increases from October 1986 rates were represented with the linear, head-dependent, Cauchy-type boundary.

Sensitivity Ranking Procedure

Stream reaches were ranked according to their simulated response to pumpage. A ranking procedure was used to classify stream–aquifer response to pumpage and identify stream reaches that are sensitive to simulated pumpage. Stream-reach sensitivity to ground-water pumpage was ranked as either high, medium, or low, using simulated stream–aquifer flow for 37 reaches in the study area. The minimum pumpage multiplier (*n*) of October 1986 rates necessary to cause stream–aquifer flow to be zero was used to rank stream reaches. A high-sensitivity rank was assigned to reaches having zero simulated stream–aquifer flow at pumpage multipliers less than 5, regardless of the scenario of ground-water or surface-water boundary conditions that imparted this effect. A medium ranking was assigned to reaches in which a scenario produced a stream–aquifer flow of zero between pumpage multipliers of 5 and 10, and a low ranking was assigned to reaches for which a scenario produced zero stream–aquifer flow at pumpage multipliers greater than 10.

Mathematical boundary conditions simulated in Torak and McDowell (1996) affect the stream-reach ranking procedure used in this study. One boundary condition represented gaining stream conditions; these reaches were expected to go dry under drought conditions. The other boundary condition represented gaining and losing stream conditions; this condition was applied to reaches that were not expected to go dry during drought conditions. Simulated stream reaches ranked high would go dry when stream–aquifer flow equals zero and when two conditions prevail: (1) the reach is simulated with a nonlinear Cauchy-type boundary and (2) the reach does not receive inflow from upstream.

Stream reaches represented with a nonlinear Cauchy-type boundary that contained simulated stream–aquifer flow for one pumpage multiplier, but were simulated as having zero stream–aquifer flow for the next higher multiplier, would have zero stream–aquifer flow at a value of the pumpage multiplier that is between the two. For example, reduction of stream–aquifer flow to zero for reach 1, Gum Creek at Coney, Ga. (fig. B1), occurred for pumpage at a multiplier larger than two (n=2), but less than five (n=5). For cases such as this, linear extrapolation of a line depicting the reduction in stream–aquifer flow by pumpage multiplier was used to estimate the minimum pumping rate at which the reach would yield zero stream–aquifer flow. The estimate of the pumpage multiplier (*n*) corresponding to zero stream–aquifer flow was calculated using the previous two pumpage multipliers and finding the zero stream–aquifer-flow intercept.

The sensitivity ranking procedure accounts for gaining and losing stream-reach conditions for stream reaches represented with a linear, Cauchy-type boundary. For reaches that contain pumpage multipliers corresponding first to gaining and then to losing reaches (fig. B23), the pumpage multiplier at which the reach changes from gaining to losing was used for ranking. Muckalee Creek near Leesburg, Ga. (reach 23, fig. B23), was ranked high because at least one scenario produced losing conditions at a pumpage multiplier less than 5.

Model Limitations

Inaccuracy associated with measurement of ground-water level, parameterization, and model application combine with errors of numerical approximation to produce models that are not exact representations of the real system. Uncertainty is introduced into model results, which require interpretation in order to make meaningful application to real-world conditions.

In this application, pumpage in wells installed through 1986 was simulated as occurring simultaneously at each well throughout the study area, a condition that does not occur, owing to the nonuniform schedules of irrigation pumpage. Also, streamflow measurements used to calibrate simulated stream–aquifer flow are instantaneous readings, taken at different times over a 6-day period. During this time, streamflow at any one station can vary significantly, and the measurements themselves contain errors of imprecision. Streamflow measurements along the Apalachicola River are long-term means for October 1986. These limitations are discussed in detail in Torak and others (1996) and Torak and McDowell (1996).

Model results can be used to show the effect of pumpage on stream–aquifer flow in Subarea 4 of the ACF River basin; however, the reader is cautioned that predictions of stream reaches going dry are based solely on computer simulation of steady-state conditions that might not actually occur in the stream–aquifer flow system.

Simulated Effect of Changing Pumpage and Boundary Conditions on Stream–Aquifer Flow

Model-derived values of stream–aquifer flow indicate that the 37 simulated stream reaches respond uniquely to changes in pumpage and boundary conditions (tables A1–A4 in Appendix A). The effects of pumpage on stream–aquifer flow for a specific reach are shown in plots of simulated stream–aquifer flow by pumpage multiplier of the October 1986 rates (figs. B1–B37 in Appendix B). The

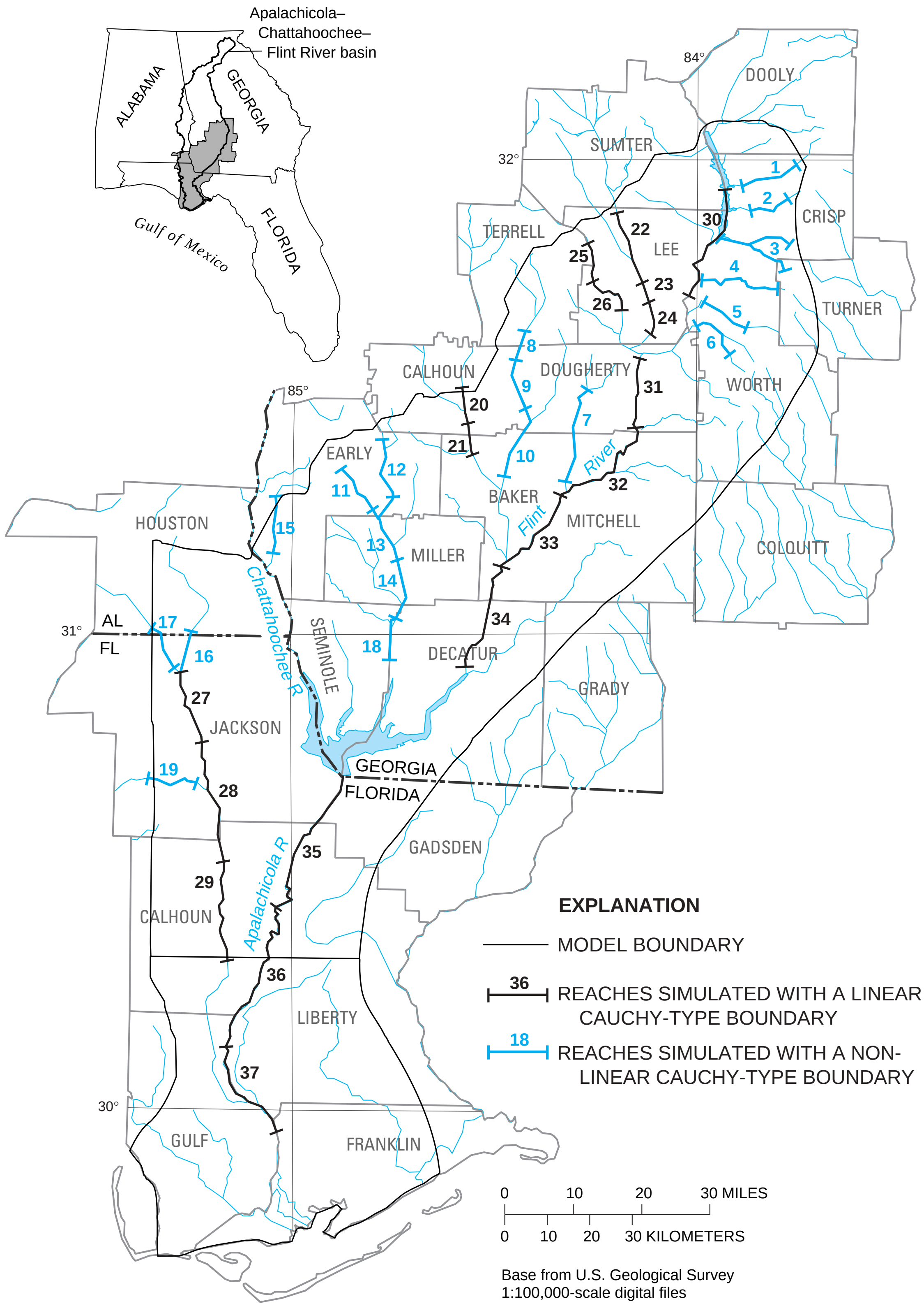


Figure 8. Model boundary and simulated stream reaches for Subarea 4, lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996).

effect of stream stage and lateral and vertical boundary conditions to the Upper Floridan aquifer on stream–aquifer flow can be observed by comparing values for a specific reach within a given table.

Of the 37 stream reaches evaluated for sensitivity, 8 reaches rank high, 13 reaches rank medium, and 16 reaches rank low in sensitivity to pumpage (table 1). Some reaches rank highly sensitive to pumpage even under normal climatic conditions. Streams ranking highly sensitive to pumpage are Gum, Jones, Cooleewahee, Spring, and Muckalee Creeks. The farthest downstream reach of the Flint River near Bainbridge, Ga. (reach 34, fig. B34), also exhibits high sensitivity to pumpage.

Stream reaches located near centers of agricultural pumpage, such as the Flint River and Dry and Spring Creeks, exhibit a large variation in stream–aquifer flow with pumpage change from October 1986 rates. Other stream reaches, such as the Apalachicola and Chipola Rivers exhibit little variation in stream–aquifer flow with pumpage change (see Appendix A, tables A1-A4 for values of stream–aquifer flow).

A reach exhibiting a high sensitivity to pumpage is Cooleewahee Creek at Newton, Ga. (reach 7, fig. B7), where stream–aquifer flow decreases for all simulations of increased pumpage from October 1986 rates for both dry and normal ground-water conditions. High sensitivity to pumpage means that stream–aquifer flow is zero at a pumpage multiplier (n) of less than 5. With stream–aquifer flow equal to zero, streamflow also is zero because there is no streamflow entering this reach from upstream. Simulation results indicate that under dry conditions, this stream would go dry with a minimal increase in pumpage from October 1986 rates.

In contrast, simulated stream–aquifer flows for reach 37 on the Apalachicola River near Sumatra, Fla. (fig. B37), indicate little effect of pumpage at any multiple of October 1986. Consequently, this reach would not be expected to go dry. Reach 37 is located far from major pumping centers in Georgia and receives water from the Intermediate system, which is pumped very little in the study area (Torak and McDowell, 1996).

Computed stream–aquifer response varied depending on whether dry or normal ground-water-flow boundaries were simulated. Normal boundary conditions produced higher stream–aquifer flow than simulations using dry boundary conditions. Simulation results indicate that stream–aquifer response is more sensitive to changes in ground-water levels than to changes in stream stage.

Simulations indicate that some stream reaches also are sensitive to pumpage during normal conditions. Reach 1, Gum Creek, may go dry under normal boundary conditions at a pumpage multiplier less than 5 times the October 1986 rate (tables A1–A4). Other stream reaches sensitive to pumpage during normal conditions are 14 and 18 on Spring Creek; 22 and 23 on Muckalee Creek; and 34 on the Flint River. Reaches 14 and 18 may go dry under a pumpage multiplier of 5; reaches 22, 23, and 34 would change from gaining stream reaches to losing stream reaches.

SIMULATED STREAM–AQUIFER FLOW IN THE VICINITY OF FEDERALLY PROTECTED FRESHWATER MUSSELS

Two field surveys in the ACF River basin during the 1990’s identified stream reaches containing federally protected mussels. The first survey was conducted during the summers of 1991 and 1992 to compare historical and present populations of mussels in the ACF River basin (Brim Box and Williams, 2000). The Joseph W. Jones Ecological Research Center, in Newton, Ga., conducted a second survey in 1999. From these data sets, the locations of six federally protected species found in the lower ACF River basin were compiled and projected on maps.

Federally protected mussel species found in the lower Apalachicola–Chattahoochee–Flint River basin
fat threeridge (*Amblema neislerii*)
shinyrayed pocketbook (*Lampsilis subangulata*)
oval pigtoe (*Pleurobema pyriforme*)
Gulf moccasinshell (*Medionidus penicillatus*)
Chipola slabshell (*Elliptio chipolaensis*)
purple bankclimber (*Elliptio sloatianus*)

Stream reaches where at least one federally protected mussel species lives are shown in figure 9 along with ranked stream reaches. Figures 10–15 show specifically where each of the six federally protected mussel species have been located in the lower ACF River basin and the sensitivity ranking of stream reaches.

Of the eight stream reaches ranked highly sensitive to pumpage, seven contain federally protected mussel species. Most reaches ranking highly sensitive to pumpage are near major pumping centers in the Dougherty Plain in Georgia. No high or medium ranks were assigned to stream reaches simulating stream–aquifer flow in the Chipola or the Apalachicola Rivers in Florida, although these reaches contain federally protected mussel species (figs. B27–B29,

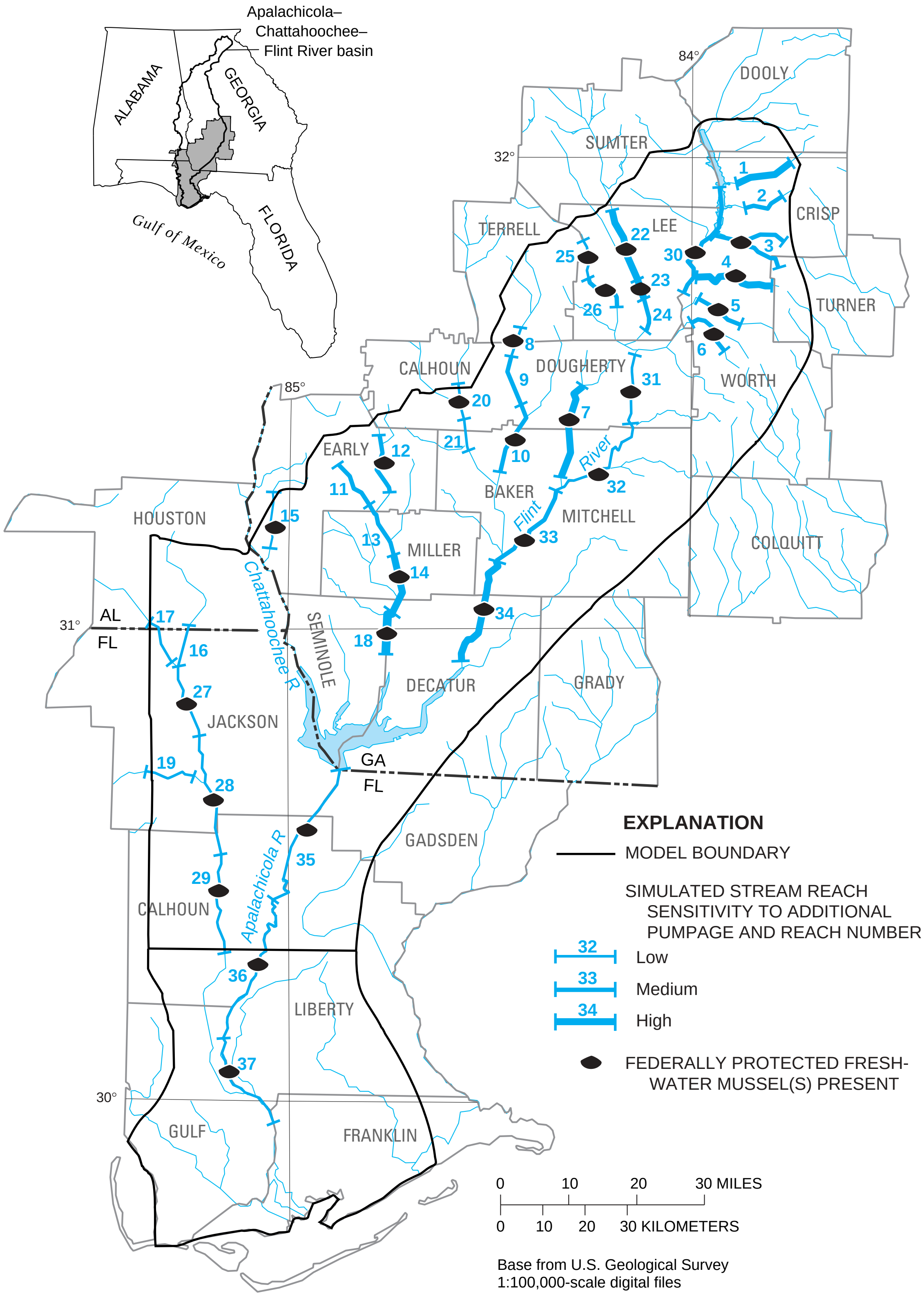


Figure 9. Model boundary, reaches where at least one federally protected freshwater mussel species is located, and simulated stream reach sensitivities in the lower Apalachicola–Chattahoochee–Flint River basin.

Table 1. Stream-reach sensitivity to pumpage and reaches where federally protected freshwater mussel species are present

[Stream sensitivity rankings: High, stream–aquifer flow equals zero for $n < 5$; Medium, stream–aquifer flow equals zero between $n = 5$ and 10; Low, stream–aquifer flow equals zero for $n > 10$; n, multiple of October 1986 pumping rate. Mussel species: sp, Shinyrayed pocketbook (*Lampsilis subangulata*); gm, Gulf moccasinshell (*Medionidus penicillatus*); op, Oval pigtoe (*Pleurobema pyriforme*); pb, Purple bankclimber (*Elliptoideus sloatianus*); cs, Chipola slabshell (*Elliptio chipolaensis*); ft, Fat threeridge (*Amblema neislerii*); leaders (—), federally protected mussel(s) not detected or reach not surveyed; do., ditto]

	Stream reach (see figure 8, page 12)	Simulated sensitivity to pumpage	Federally protected mussel(s) in reach
01	Gum Creek[1/]	High	—
02	Cedar Creek[1/]	Medium	—
03	Swift Creek[1/]	do.	gm
04	Jones Creek[1/]	High	sp, op
05	Abrams Creek[1/]	Medium	sp
06	Mill Creek[1/]	do.	sp, pb
07	Cooleewahee Creek[1/]	High	sp, op
08	Chickasawhatchee Creek[1/]	Low	sp, gm, op
09	Do.[1/]	Medium	—
10	Chickasawhatchee Creek[1/]	do.	sp, gm
11	Dry Creek (Georgia)[1/]	do.	—
12	Spring Creek[1/]	do.	sp
13	Do.[1/]	do.	—
14	Do.[1/]	High	sp
15	Sawhatchee Creek[1/]	Low	sp
16	Cowarts Creek[1/]	do.	—
17	Marshall Creek[1/]	do.	—
18	Spring Creek[1/]	High	sp
19	Dry Creek (Florida)[1/]	Low	—
20	Ichawaynochaway Creek	do.	sp
21	Do.	do.	—
22	Muckalee Creek	High	sp, gm, op,
23	Do.	do.	sp
24	Do.	Medium	—
25	Kinchafoonee Creek[2/]	Low	sp, op
26	Do.	Medium	sp
27	Chipola River	Low	op
28	Do.	do.	op, cs
29	Do.	do.	sp, cs
30	Flint River	Medium	pb
31	Do.	Low	pb
32	Do.	do.	gm, pb
33	Do.	Medium	pb
34	Do.	High	pb
35	Apalachicola River	Low	pb, ft
36	Do.	do.	pb, ft
37	Do.	do.	pb, ft

[1/]Simulated as nonlinear leakage condition; zero-value entries may occur at pumpage multiplier (n) less than indicated on table.

[2/]Stream–aquifer flow is negative for all values of n.

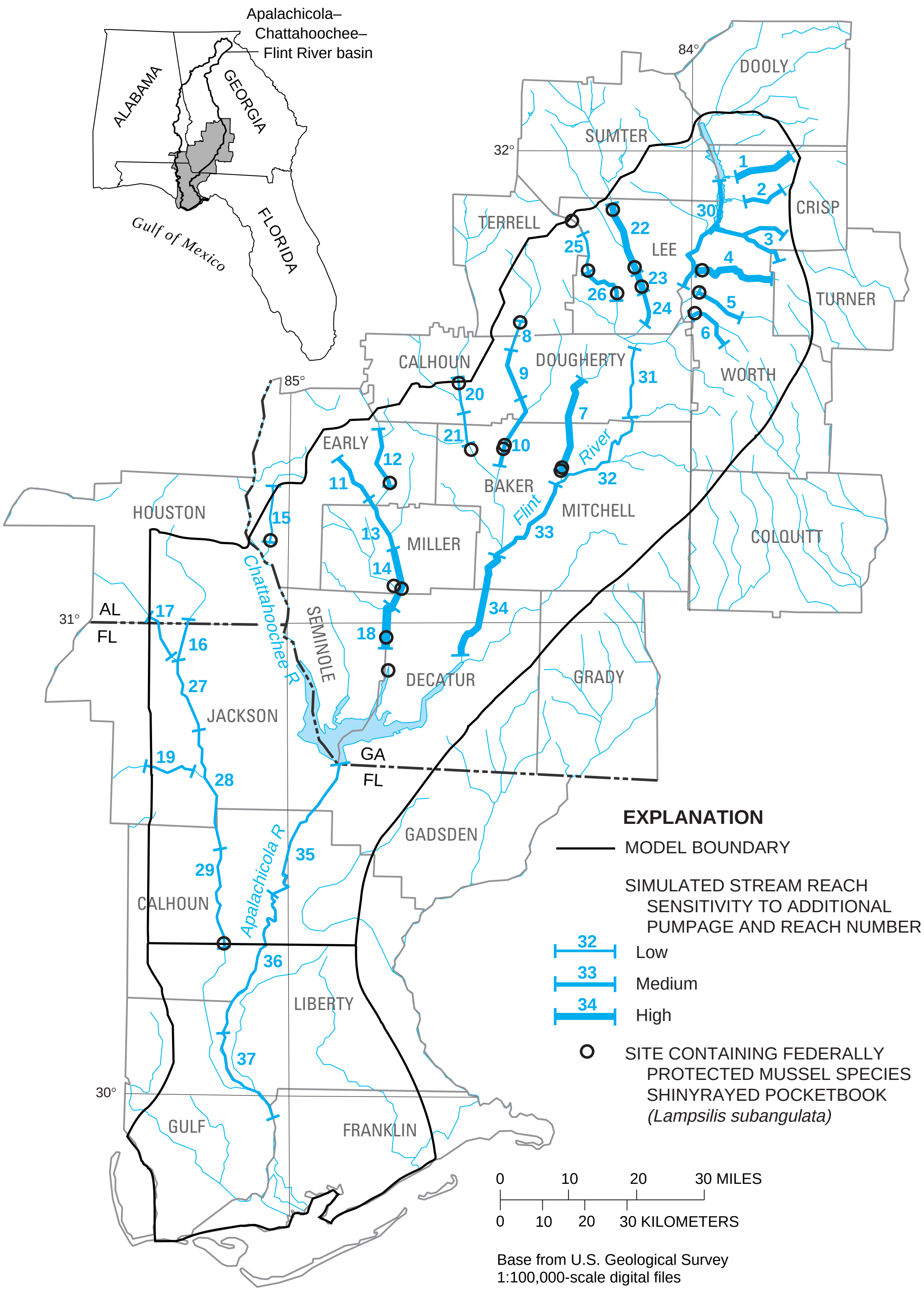


Figure 10. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Shinyrayed pocketbook (*Lampsilis subangulata*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000; Paul M. Johnson, Joseph W. Jones Ecological Research Center, written commun., 1999).

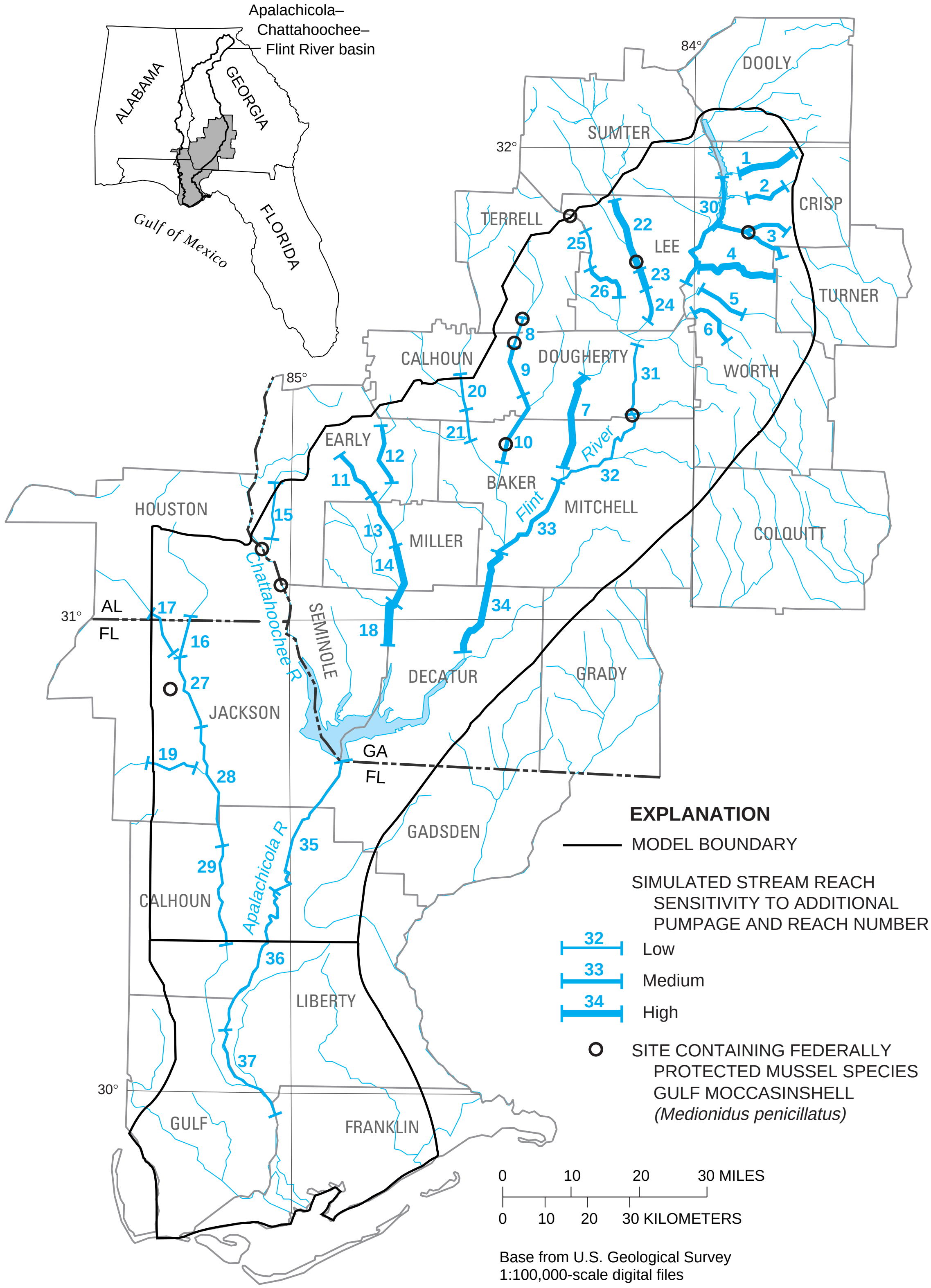


Figure 11. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Gulf moccasinshell (*Medionidus penicillatus*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000; Paul M. Johnson, Joseph W. Jones Ecological Research Center, written commun., 1999).

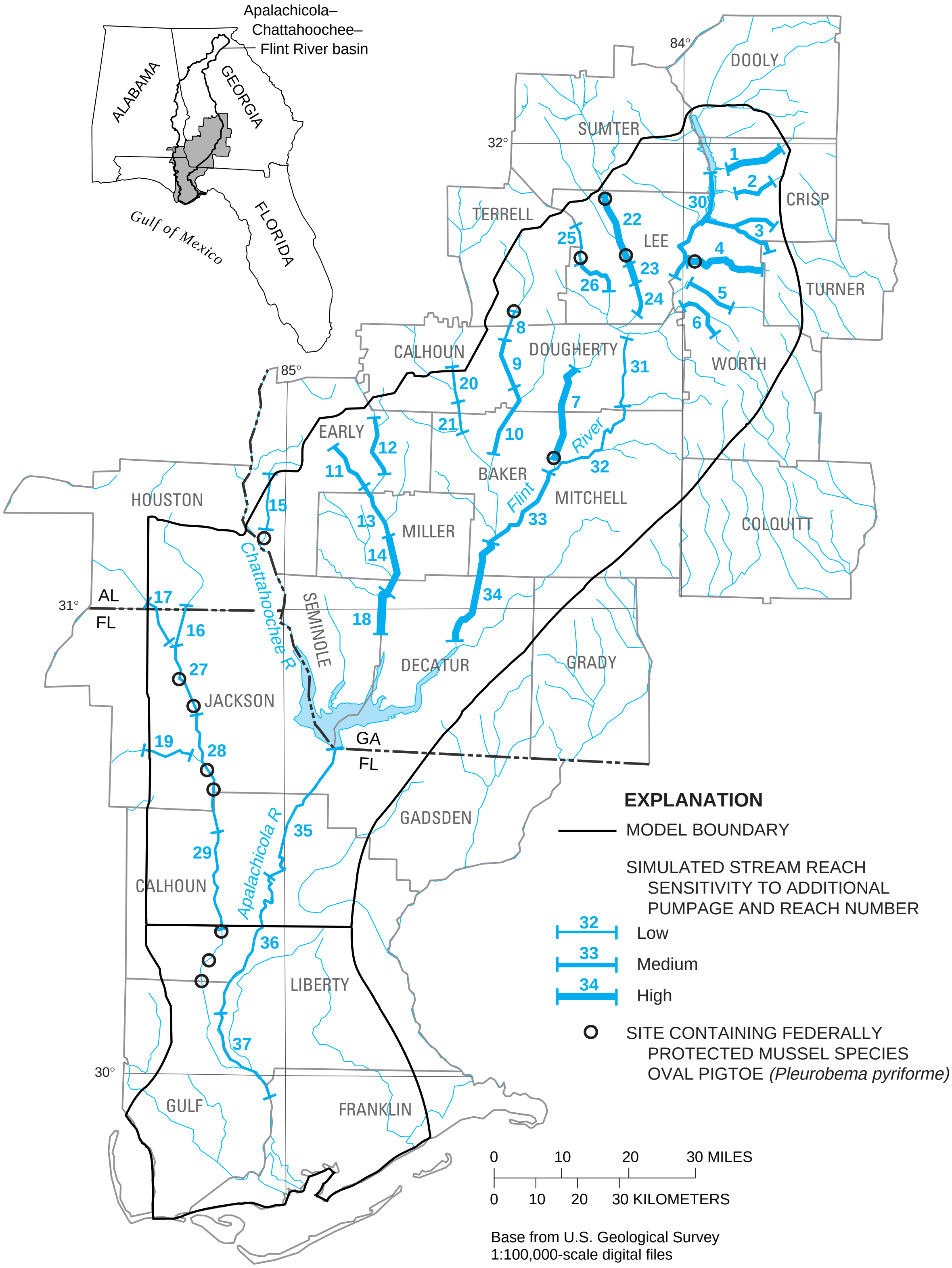


Figure 12. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Oval pigtoe (*Pleurobema pyriforme*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000; Paul M. Johnson, Joseph W. Jones Ecological Research Center, written commun., 1999).

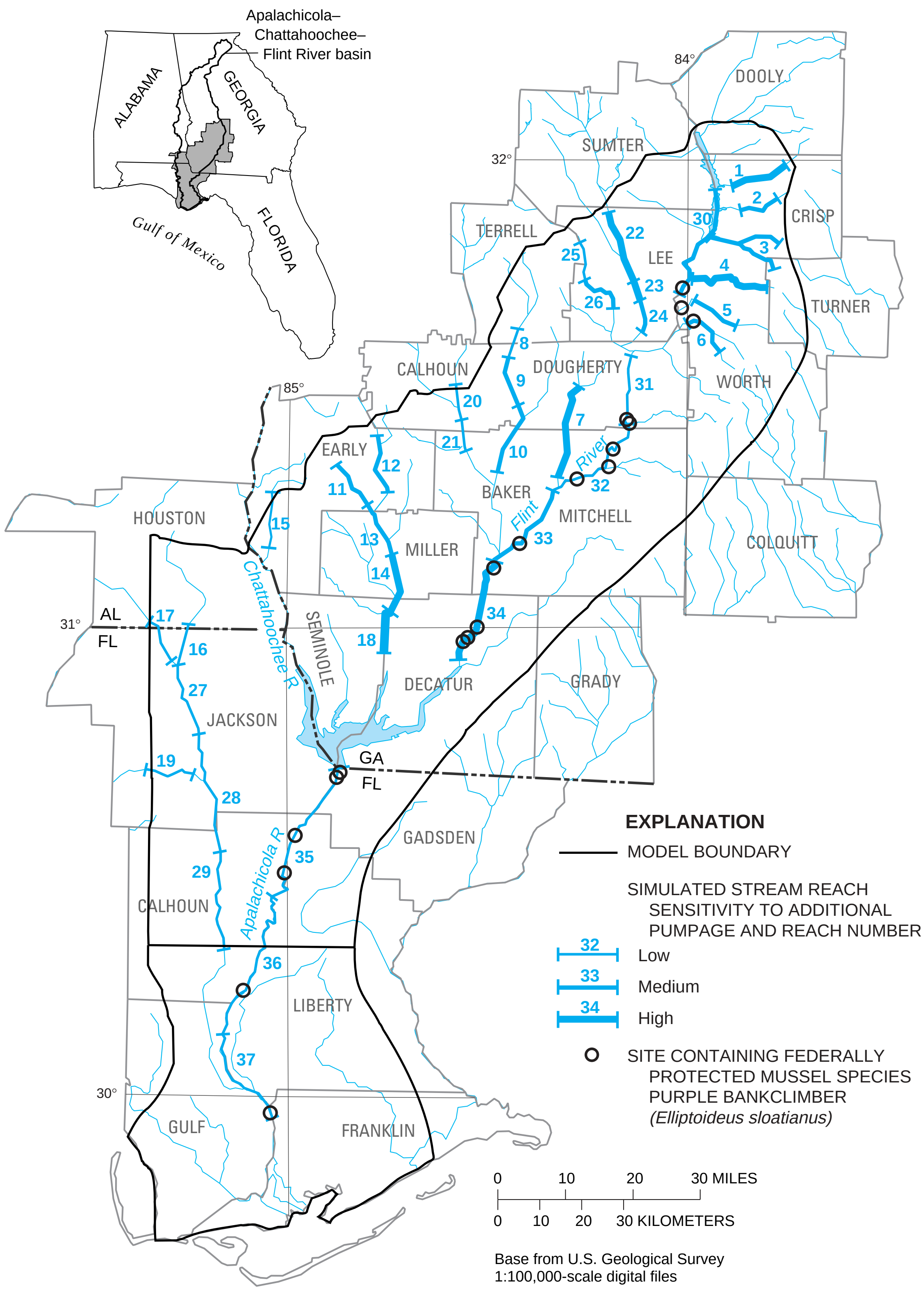


Figure 13. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Purple bankclimber (*Elliptoideus sloatianus*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000).

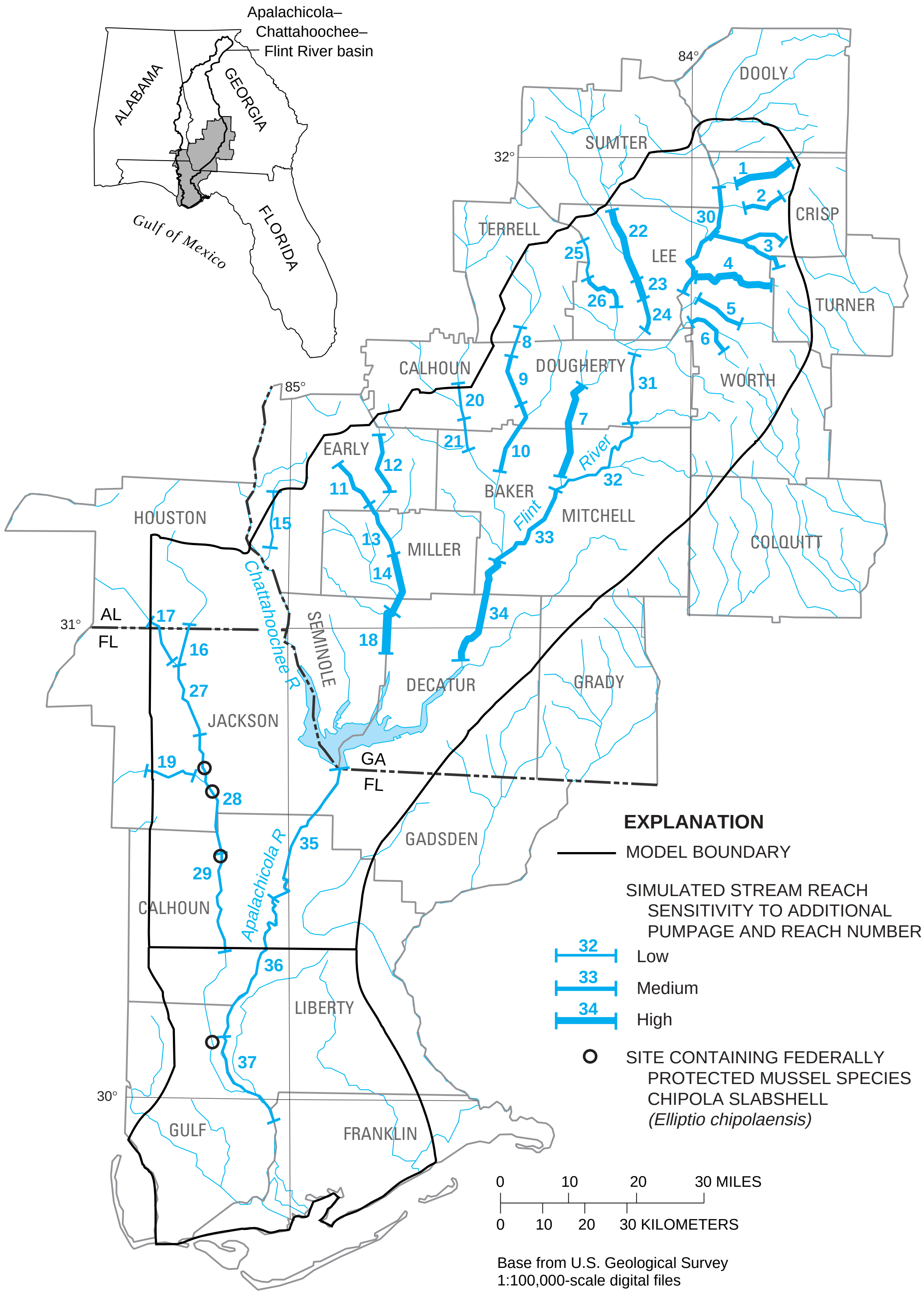


Figure 14. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Chipola slabshell (*Elliptio chipolaensis*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000).

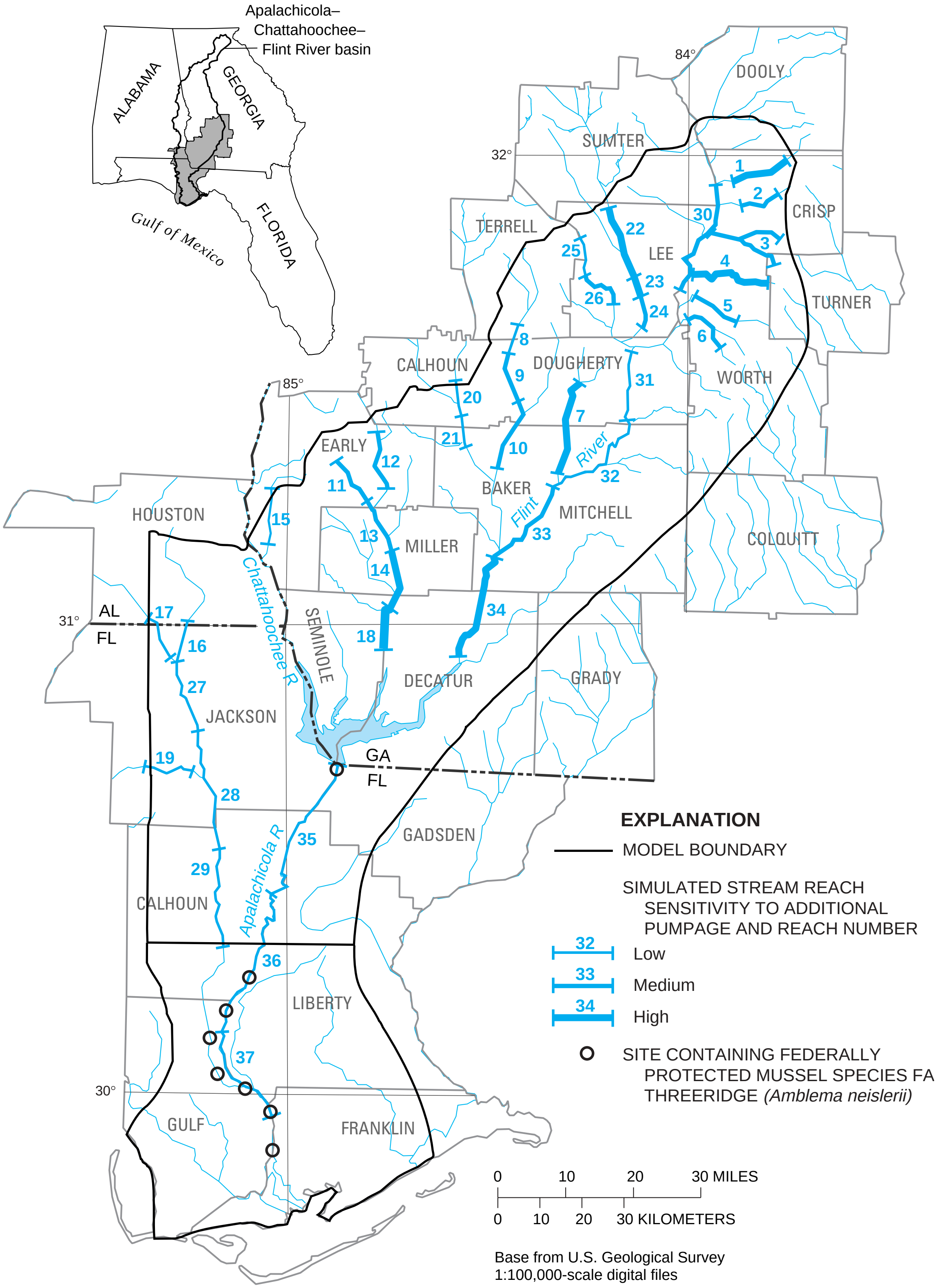


Figure 15. Model boundary and simulated stream reach sensitivities for the lower Apalachicola–Chattahoochee–Flint River basin (modified from Torak and McDowell, 1996) and sites containing federally protected mussel species Fat threeridge (*Amblema neislerii*) (Amy J. Benson, U.S. Geological Survey, written commun., 2000).

and B35–B37); these stream reaches are far removed from major pumping centers in Georgia.

Model simulations indicate increased pumpage would substantially effect mussel habitat in stream reaches ranked highly sensitive to pumpage and that have no inflow from upstream. Long-term, pumpage-induced, stream–aquifer flow reductions would cause small tributary streams such as Gum, Jones, and Cooleewahee Creeks to go dry, because these reaches have no inflow from upstream. These streams, except for Gum Creek, provide habitat for federally protected mussel species. Other stream reaches with high rankings could go dry depending on the upstream flow entering the reach. Drying conditions in these streams would reduce available habitat; and thus contribute to further declines in federally protected mussel species (U.S. Fish and Wildlife Service, 1998; Richard J. Neves, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Polytechnic Institute and State University, oral commun., 2001).

SUMMARY AND CONCLUSIONS

Simulation results indicate that ground-water withdrawal in the lower Apalachicola–Chattahoochee–Flint (ACF) River basin during times of drought could reduce stream–aquifer flow and cause specific stream reaches to go dry. Of the 37 reaches that were studied, 8 reaches ranked highly sensitive to pumpage, 13 reaches ranked medium, and 16 reaches ranked low. Of the eight reaches that ranked high, seven contain at least one federally protected mussel species. Model simulations indicate small tributary streams such as Gum, Jones, Muckalee, Spring, and Cooleewahee Creeks would go dry at lower pumping rates than needed to dry up larger streams. Other streams that were ranked high may go dry depending on the amount of upstream flow entering the reach; this condition is indicated for some reaches on Spring Creek. A dry stream condition is of particular concern to water and wildlife managers because adequate streamflow is essential to mussel survival (Dick Neves, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Polytechnic Institute and State University, oral commun., 200l; U.S. Fish and Wildlife Service, 1998).

Besides being sensitive to dry conditions, some streams exhibit a high sensitivity to pumpage under normal conditions. Reach 1, Gum Creek, may go dry under normal boundary conditions at a pumpage multiplier less than 5 times the October 1986 rate. Other stream reaches sensitive to pumpage during normal conditions are 14 and 18 on Spring Creek; 22 and 23 on Muckalee Creek; and 34 on the Flint River. Reaches 14, 18, 22, 23, and 34 in the simulation would switch from gaining to losing stream conditions.

Stream reaches in Florida show low sensitivity to pumpage because nearly all simulated pumpage occurs in Georgia, far from stream reaches in Florida that were expected to show pumpage-induced streamflow reductions. Stream reaches 36 and 37 simulated in the Intermediate model ranked low because they are far from pumpage in Georgia and also because they are in hydraulic connection with the Intermediate system, not the Upper Floridan aquifer in which most pumpage occurs.

Limitations posed by the modeling process and measurements used to calibrate the models prevent definitive statements from being made about the exact pumpage required to cause streams containing federally protected mussels to go dry. The ranking of stream reaches conducted in this study, however, can be used as an indicator of the degree to which pumpage affects change stream–aquifer flow in streams containing federally protected mussel species.

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APPENDIX A

TABLES LISTING STREAM–AQUIFER FLOW, BY REACH, FOR SIMULATED HYDROLOGIC AND PUMPAGE CONDITIONS

Table A1. Stream–aquifer flow, by reach, for hydrologic conditions and pumpage at 0.5 times October 1986 rates simulated in the Subarea 4 model

[Do., ditto; negative values indicate recharge to aquifer by streamflow; Oct 86 is October 1986 streamflow; Q_{90} is streamflow that is exceeded 90 percent of the time, and Q_{50} is streamflow that is exceeded 50 percent of the time; streamflow conditions calculated using recorded measurements for period of record ending 1993; dry is October 1986 conditions of lateral boundary and semiconfining-unit head; normal is long-term-average conditions of lateral boundary and semiconfining-unit head]

	Stream reach (see figure 8, page 12)	Computed net stream–aquifer flow (in cubic feet per second)					
		Hydrologic condition					
		Oct 86 Dry	Oct 86 Normal	Q_{90} Dry	Q_{90} Normal	O_{50} Dry	Q_{50} Normal
1	Gum Creek[1/]	4.5	6	5.3	7	4.3	6
2	Cedar Creek[1/]	1.4	1.9	1.4	1.9	1.1	1.5
3	Swift Creek[1/]	4	5.3	4	5.3	3.4	4.6
4	Jones Creek[1/]	2.6	3.4	2.8	3.6	2.6	3.2
5	Abrams Creek[1/]	2.9	3.7	2.9	3.7	2.8	3.6
6	Mill Creek[1/]	7.3	9.4	7.3	9.4	7.0	8.8
7	Cooleewahee Creek[1/]	0.8	4.6	0.6	4.2	0.2	3.1
8	Chickasawhatchee Creek[1/]	4	5.7	4	5.6	3.6	5.3
9	Do.[1/]	0.5	4	0.3	3.9	0.2	3.4
10	Do.[1/]	3.1	10.5	2.9	10.4	2.8	9.7
11	Dry Creek (Georgia)[1/]	3.1	4.6	2.9	4.5	3.1	4.6
12	Spring Creek[1/]	3.9	6	3.9	5.9	4	6
13	Do.[1/]	24.9	36.4	23.8	35.4	25.2	36.8
14	Do.[1/]	4	6.8	3.6	6.3	4.6	7.4
15	Sawhatchee Creek[1/]	9.7	15.6	9.7	15.6	9.1	14.9
16	Cowarts Creek[1/]	20	26.8	19.8	26.6	19	25.8
17	Marshall Creek[1/]	31.7	46.1	31.4	46	30.2	44.7
18	Spring Creek[1/]	52.9	59.9	51.5	58.3	54.8	61.7
19	Dry Creek (Florida)[1/]	42.2	74.1	41.6	73.3	39.2	70.1
20	Ichawaynochaway Creek	53.7	78.9	52.3	77.4	50.1	75.2
21	Do.	24.4	35.7	24.1	35.4	23.7	34.8
22	Muckalee Creek	23.2	29.7	20	26.2	19	25.2
23	Do.	5.7	7.3	5	6.3	4.6	6
24	Do.	15	18	11.1	14.1	10.1	13
25	Kinchafoonee Creek	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
26	Do.	6.7	7.3	7	7.4	6.7	7.4
27	Chipola River	115.1	171.3	113.7	169.9	108	164.2
28	Do.	339.8	387.3	361.6	409	448.9	496.3
29	Do.	359.2	388.7	455.9	485.4	678.4	708
30	Flint River	7.3	8.4	7.4	8.5	7.3	8.4
31	Do.	629.8	708	630.3	708.3	616.5	694.2
32	Do.	564.5	644.2	558.9	638.6	534.6	613.6
33	Do.	396.5	501.8	391.5	496.9	376.3	481.4
34	Do.	394.3	452.8	393.2	451.5	377.1	435
35	Apalachicola River	282.1	334.7	268.3	321.1	256.6	309.3
36	Do.	165.6	210	148.4	197.2	116.1	160.5
37	Do.	522.6	534.2	480.6	480.8	92.7	181.5

[1/]Simulated as nonlinear leakage condition.

Table A2. Stream–aquifer flow, by reach, for hydrologic conditions and pumpage at October 1986 rates simulated in the Subarea 4 model

[Do., ditto; negative values indicate recharge to aquifer by streamflow; Oct 86 is October 1986 streamflow; Q_{90} is streamflow that is exceeded 90 percent of the time, and Q_{50} is streamflow that is exceeded 50 percent of the time; streamflow conditions calculated using recorded measurements for period of record ending 1993; dry is October 1986 conditions of lateral boundary and semiconfining-unit head; normal is long-term-average conditions of lateral boundary and semiconfining-unit head]

Stream reach (see figure 8, page 12)		Computed net stream–aquifer flow (in cubic feet per second)					
		Hydrologic condition					
		Oct 86 Dry	Oct 86 Normal	Q_{90} Dry	Q_{90} Normal	O_{50} Dry	Q_{50} Normal
1	Gum Creek[1/]	3.6	5.1	4.2	5.7	3.4	5
2	Cedar Creek[1/]	1.2	1.7	1.2	1.7	0.9	1.5
3	Swift Creek[1/]	3.9	5	3.9	5	3.2	4.3
4	Jones Creek[1/]	2.3	2.9	2.5	2.9	2.2	2.9
5	Abrams Creek[1/]	2.6	3.4	2.6	3.4	2.5	3.2
6	Mill Creek[1/]	7	8.8	6.8	8.8	6.3	8.4
7	Cooleewahee Creek[1/]	0.5	4	0.5	3.7	0	2.6
8	Chickasawhatchee Creek[1/]	4	5.7	4	5.6	3.6	5.3
9	Do.[1/]	0.3	4	0.3	3.9	0.2	3.2
10	Do.[1/]	2.8	10.1	2.6	9.7	2.5	9.3
11	Dry Creek (Georgia)[1/]	2.8	4.3	2.6	4.2	2.8	4.3
12	Spring Creek[1/]	3.6	5.7	3.4	5.6	3.6	5.7
13	Do.[1/]	19.5	31.3	18.6	30.3	20	31.6
14	Do.[1/]	1.1	3.1	0.8	2.6	1.4	3.6
15	Sawhatchee Creek[1/]	9.6	15.3	9.6	15.3	8.8	14.7
16	Cowarts Creek[1/]	20	26.6	19.7	26.5	18.9	25.7
17	Marshall Creek[1/]	31.6	46.1	31.3	45.8	30	44.6
18	Spring Creek[1/]	42.2	49.5	40.7	48	44.3	51.2
19	Dry Creek (Florida)[1/]	42.1	74	41.6	73.3	39	70.1
20	Ichawaynochaway Creek	52.6	77.8	51.2	76.4	49.1	74.1
21	Do.	23.7	35	23.4	34.7	22.9	34.2
22	Muckalee Creek	17.8	24.3	14.5	21.0	13.6	20
23	Do.	3.9	5.6	3.1	4.6	2.8	4.3
24	Do.	14.2	17.3	10.4	13.5	9.4	12.4
25	Kinchafoonee Creek	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
26	Do.	5.9	6.7	6.2	6.8	6	6.7
27	Chipola River	114.7	170.8	113.3	169.4	107.5	163.7
28	Do.	339.5	387	361.2	408.7	448.6	496
29	Do.	359	388.7	455.7	485.4	678.2	707.8
30	Flint River	6.3	7.4	6.5	7.6	6.3	7.3
31	Do.	604.7	683.2	605.4	683.5	591.4	669.4
32	Do.	537.1	616.8	531.7	611.2	507.3	586.3
33	Do.	363.3	469.5	358.5	464.5	343.4	449.1
34	Do.	352	411.9	351	410.8	335.5	394.8
35	Apalachicola River	281.5	334.2	267.7	320.5	255.9	308.7
36	Do.	165.4	209.8	148.1	197	115.9	160.3
37	Do.	522.6	534.2	480.6	480.8	92.7	181.5

[1/]Simulated as nonlinear leakage condition.

Table A3. Stream–aquifer flow, by reach, for hydrologic conditions and pumpage at 2 times October 1986 rates simulated in the Subarea 4 model

[Do, ditto; negative values indicate recharge to aquifer by streamflow; Oct 86 is October 1986 streamflow; Q_{90} is streamflow that is exceeded 90 percent of the time, and Q_{50} is streamflow that is exceeded 50 percent of the time; streamflow conditions calculated using recorded measurements for period of record ending 1993; dry is October 1986 conditions of lateral boundary and semiconfining-unit head; normal is long-term-average conditions of lateral boundary and semiconfining-unit head]

	Stream reach (see figure 8, page 12)	Computed net stream–aquifer flow (in cubic feet per second)					
		Hydrologic condition					
		Oct 86 Dry	Oct 86 Normal	Q_{90} Dry	Q_{90} Normal	O_{50} Dry	Q_{50} Normal
1	Gum Creek[1/]	1.7	3.2	2.2	3.7	1.5	2.9
2	Cedar Creek[1/]	0.9	1.4	0.9	1.4	0.8	1.2
3	Swift Creek[1/]	3.4	4.6	3.2	4.5	2.8	3.9
4	Jones Creek[1/]	1.5	2.2	1.5	2.2	1.4	2
5	Abrams Creek[1/]	1.9	2.6	1.9	2.6	1.5	2.5
6	Mill Creek[1/]	5.9	7.7	5.9	7.7	5.6	7.3
7	Cooleewahee Creek[1/]	0.2	3.1	0.2	2.8	0	2
8	Chickasawhatchee Creek[1/]	4	5.7	3.9	5.6	3.6	5.1
9	Do.[1/]	0.3	3.7	0.3	3.6	0.2	2.9
10	Do.[1/]	2.3	9.1	2.2	8.8	2	8.4
11	Dry Creek (Georgia)[1/]	2.2	3.9	2.2	3.7	2.3	3.9
12	Spring Creek[1/]	2.6	4.8	2.5	4.6	2.6	5
13	Do.[1/]	9.1	20.4	8.4	19.7	9.4	20.9
14	Do.[1/]	0	0.2	0	0	0	0.2
15	Sawhatchee Creek[1/]	9.1	15.2	9.1	15	8.5	14.4
16	Cowarts Creek[1/]	19.7	26.5	19.3	26.3	18.6	25.5
17	Marshall Creek[1/]	31.4	46	31.1	45.6	30	44.4
18	Spring Creek[1/]	15.3	25.5	14.1	24.1	18	28
19	Dry Creek (Florida)[1/]	41.9	73.8	41.3	73	38.8	69.9
20	Ichawaynochaway Creek	50.3	75.7	48.9	74.1	46.7	72
21	Do.	22.1	33.6	21.7	33.1	21.4	32.8
22	Muckalee Creek	7	13.5	3.9	10.2	2.8	9.1
23	Do.	0.2	1.9	-0.6	0.9	-0.8	0.8
24	Do.	12.5	15.9	8.8	12.1	7.9	11
25	Kinchafoonee Creek	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
26	Do.	4.3	5.3	4.6	5.4	4.6	5.3
27	Chipola River	113.6	169.9	112.2	168.5	106.6	162.8
28	Do.	338.7	386.4	360.4	408.1	447.8	495.3
29	Do.	358.9	388.6	455.6	485.3	678.1	707.8
30	Flint River	4.3	5.6	4.5	5.6	4.3	5.4
31	Do.	554.6	633.7	555.2	634.1	541.5	619.9
32	Do.	482.2	562	476.8	556.5	452.8	531.7
33	Do.	294.9	403.1	290.1	398.3	275.3	383.2
34	Do.	259.4	323.9	258.4	323.0	243.9	307.8
35	Apalachicola River	280.2	333	266.5	319.2	254.9	307.5
36	Do.	165	209.4	147.8	196.4	115.3	159.9
37	Do.	522.6	534.2	480.6	480.8	92.7	181.5

[1/]Simulated as nonlinear leakage condition.

Table A4. Stream–aquifer flow, by reach, for hydrologic conditions and pumpage at 5 times October 1986 rates simulated in the Subarea 4 model

[Do., ditto; negative values indicate recharge to aquifer by streamflow; Oct 86 is October 1986 streamflow; Q_{90} is streamflow that is exceeded 90 percent of the time, and Q_{50} is streamflow that is exceeded 50 percent of the time; streamflow conditions calculated using recorded measurements for period of record ending 1993; dry is October 1986 conditions of lateral boundary and semiconfining-unit head; normal is long-term-average conditions of lateral boundary and semiconfining-unit head]

	Stream reach (see figure 8, page 12)	Computed net stream–aquifer flow (in cubic feet per second)					
		Hydrologic condition					
		Oct 86 Dry	Oct 86 Normal	Q_{90} Dry	Q_{90} Normal	O_{50} Dry	Q_{50} Normal
1	Gum Creek[1/]	0	0	0	0	0	0
2	Cedar Creek[1/]	0.2	0.6	0.2	0.6	0.2	0.5
3	Swift Creek[1/]	2.2	3.2	2	3.2	1.5	2.6
4	Jones Creek[1/]	0	0.2	0	0.3	0	0.2
5	Abrams Creek[1/]	0.2	0.8	0.2	0.8	0.2	0.5
6	Mill Creek[1/]	3.1	5.0	2.9	4.8	2.6	4.3
7	Cooleewahee Creek[1/]	0	1.1	0	0.9	0	0.5
8	Chickasawhatchee Creek[1/]	3.9	5.6	3.9	5.4	3.4	5.0
9	Do.[1/]	0.3	2.9	0.2	2.6	0.2	2.2
10	Do.[1/]	0.8	5.9	0.8	5.7	0.6	5.3
11	Dry Creek (Georgia)[1/]	0.5	1.7	0.5	1.5	0.5	1.9
12	Spring Creek[1/]	0.5	2.2	0.5	1.9	0.5	2.2
13	Do.[1/]	0.8	2.2	0.6	1.9	0.8	2.2
14	Do.[1/]	0	0	0	0	0	0
15	Sawhatchee Creek[1/]	7.9	13.8	7.9	13.8	7.3	13.2
16	Cowarts Creek[1/]	18.9	25.8	18.7	25.5	18.0	24.8
17	Marshall Creek[1/]	30.9	45.3	30.6	45	29.4	43.9
18	Spring Creek[1/]	0	0	0	0	0	0
19	Dry Creek (Florida)[1/]	41.3	73	40.7	72.4	38.2	69.2
20	Ichawaynochaway Creek	42.7	68.7	41.3	67.3	39.3	65.1
21	Do.	16.6	28.6	16.2	28.3	15.9	27.9
22	Muckalee Creek	-17.5	-12.5	-21.8	-17.6	-22.6	-18.7
23	Do.	-8.0	-6.7	-9.1	-8.0	-9.1	-8.4
24	Do.	8.7	12.1	5	8.0	3.9	7
25	Kinchafoonee Creek	-2.3	-2.3	-2.3	-2.3	-2.3	-2.3
26	Do.	0.9	1.2	0.8	0.8	0.6	0.6
27	Chipola River	110.2	166.8	108.8	165.4	103.2	159.7
28	Do.	336.4	384.2	358.1	405.9	445.5	493.2
29	Do.	358.4	388.1	455.1	484.7	677.6	707.2
30	Flint River	0.2	0.9	0.2	0.9	0.2	0.6
31	Do.	403	484.5	403.6	485	390.4	471
32	Do.	314.9	396.8	309.8	391.4	286.7	367.1
33	Do.	74.6	190.6	69.9	185.7	56.2	171.3
34	Do.	-76.1	-2.5	-77.2	-3.9	-89.8	-15.9
35	Apalachicola River	275.9	328.8	262.1	315.1	250.4	303.3
36	Do.	163.6	208	146.4	195	113.9	158.5
37	Do.	522.6	534.2	480.6	480.8	92.7	181.5

[1/]Simulated as nonlinear leakage condition.

APPENDIX B

GRAPHS SHOWING THE SIMULATED EFFECT OF PUMPAGE ON STREAM–AQUIFER FLOW FOR STREAM REACHES 1–37

EXPLANATION FOR FIGURES B1–B37

NOTE: Graph scales vary

Ground-water boundary condition	Stream stage for flow condition—dashed where extrapolated		
	October 1986	[1]Q90	[2]Q50
Dry (October 1986)	—— □ - - -	—— □ - - -	—— △ - - -
Normal (Long-term average)	—— ■ - - -	—— ■ - - -	—— ▲ - - -

[1] Streamflow equal to or exceeded 90 percent of the time (low-flow condition)

[2] Streamflow equal to or exceeded 50 percent of the time (median streamflow condition)

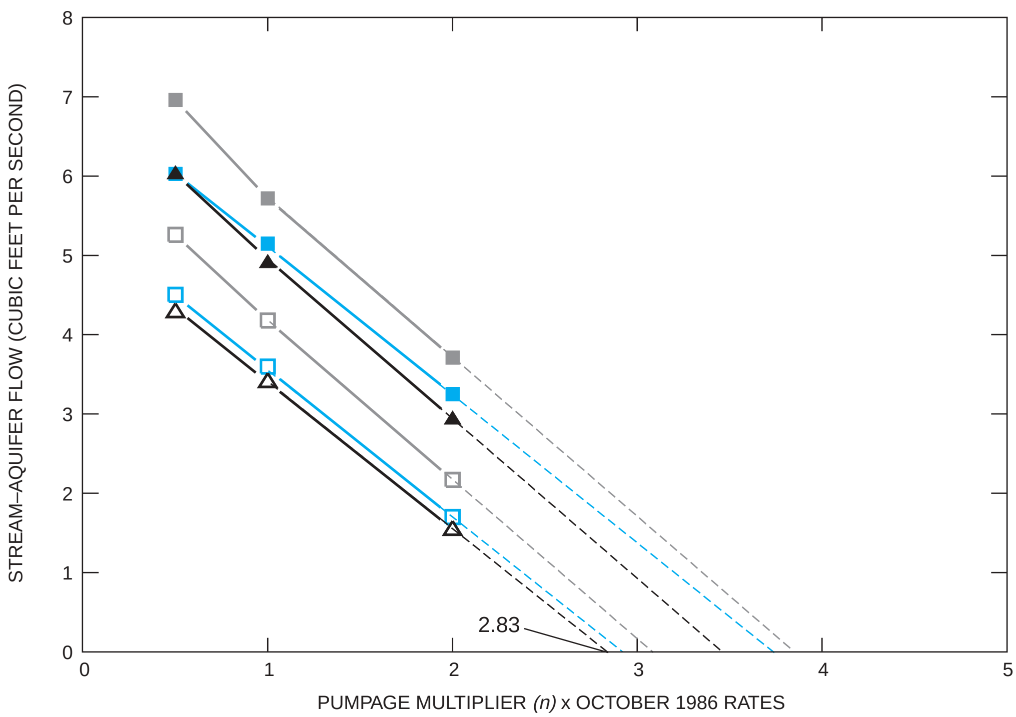

Figure B1. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 1, Gum Creek, Georgia (see fig. 8 for location).

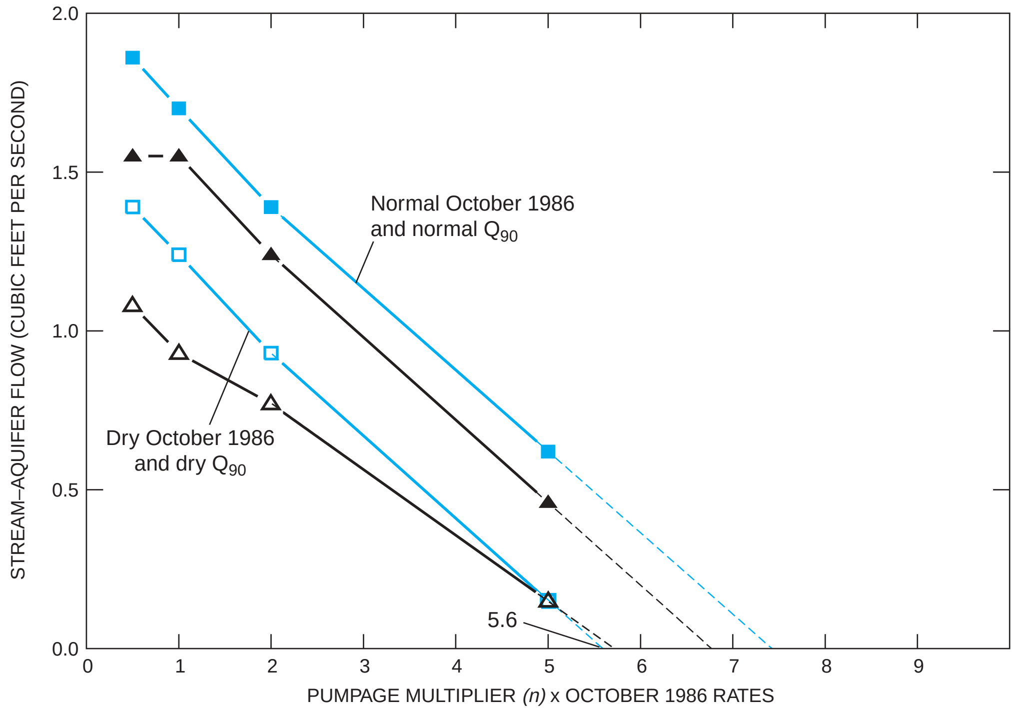

Figure B2. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 2, Cedar Creek, Georgia (see fig. 8 for location).

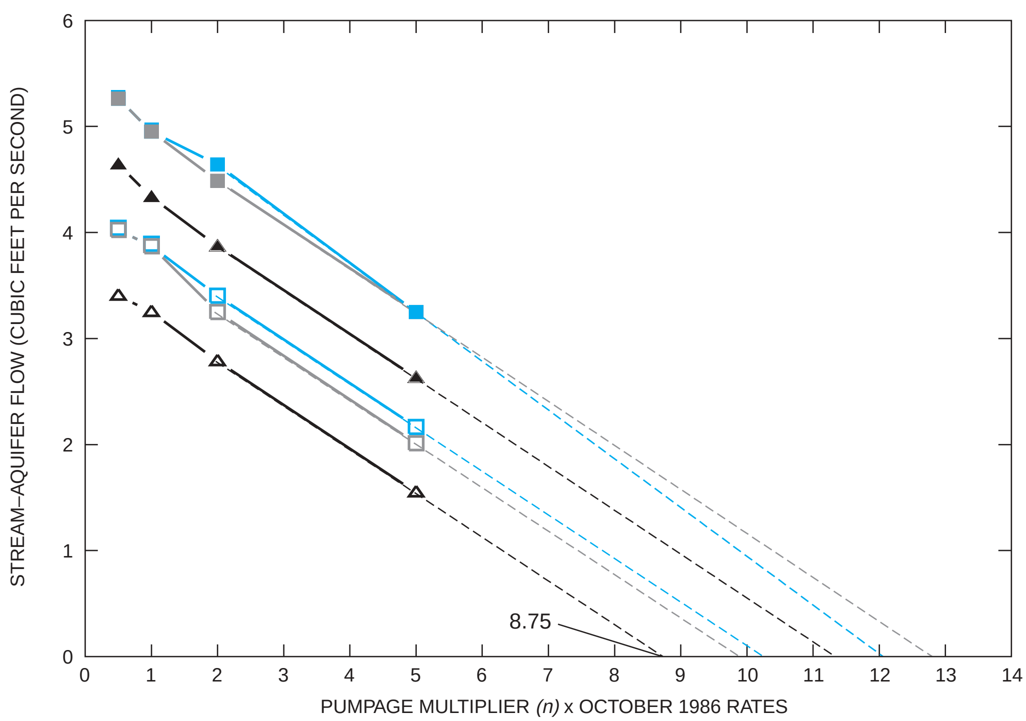

Figure B3. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 3, Swift Creek, Georgia (see fig. 8 for location).

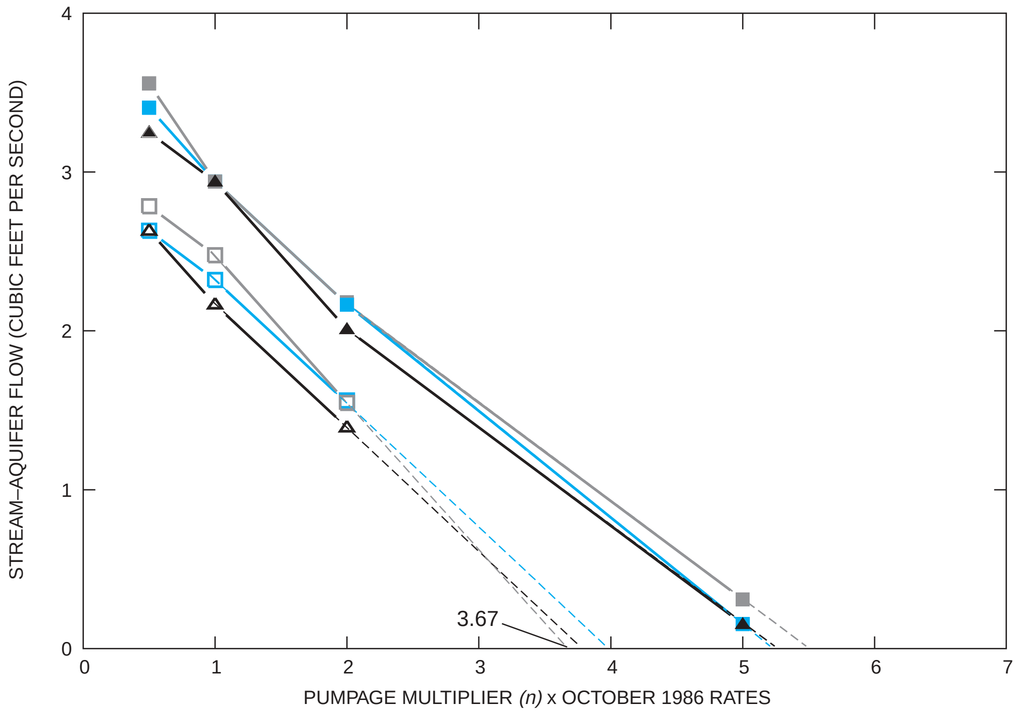

Figure B4. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 4, Jones Creek, Georgia (see fig. 8 for location).

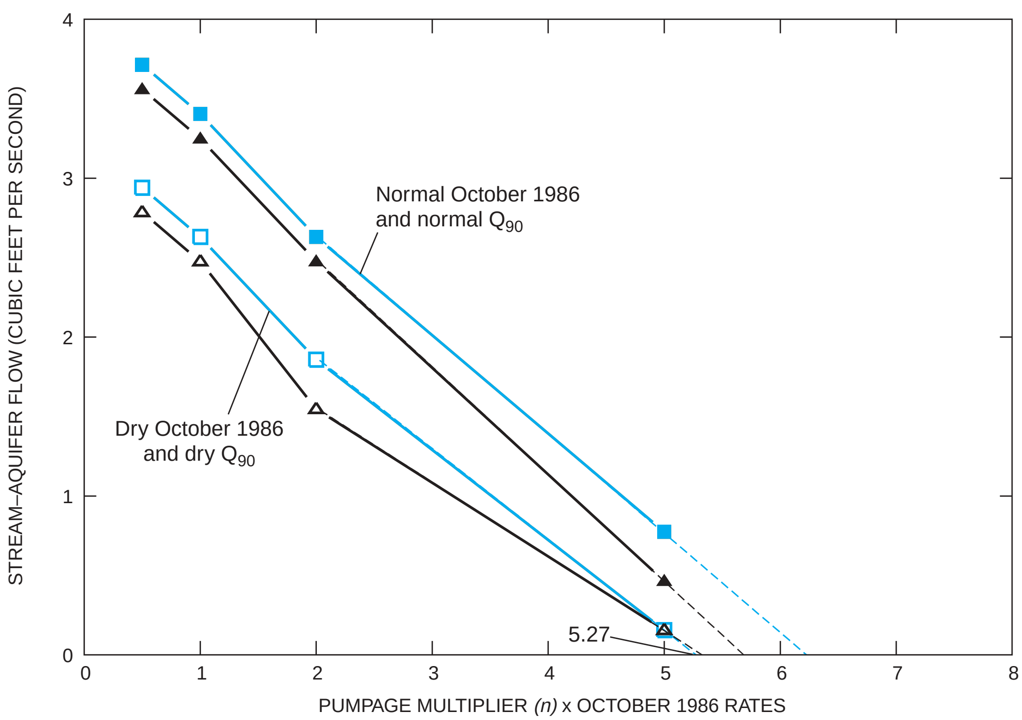

Figure B5. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 5, Abrams Creek, Georgia (see fig. 8 for location).

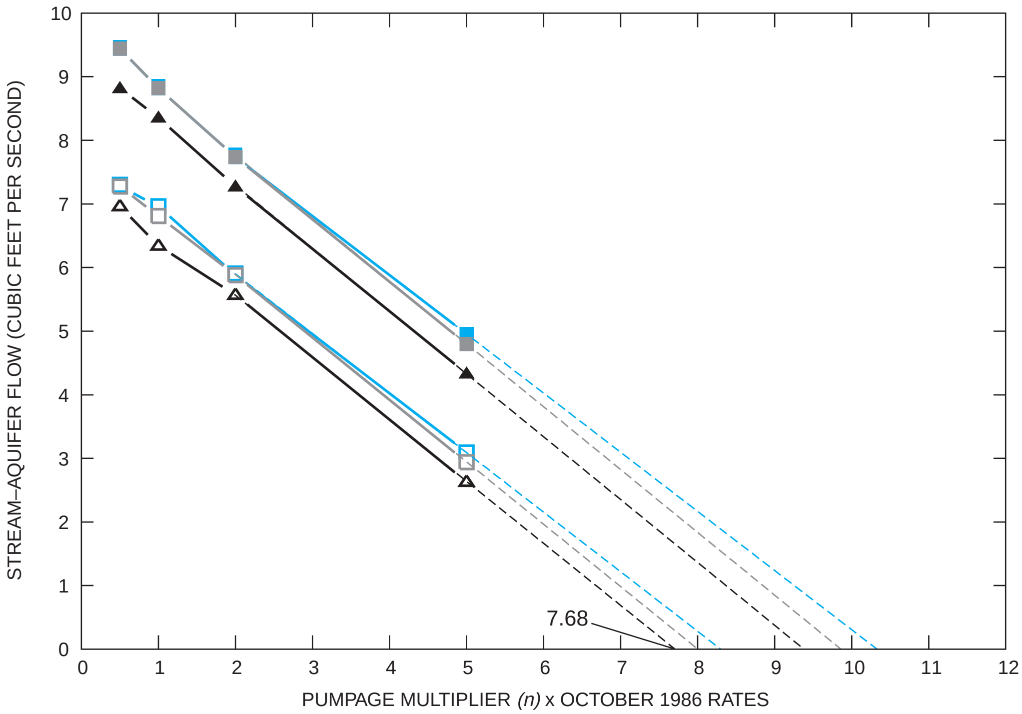

Figure B6. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 6, Mill Creek, Georgia (see fig. 8 for location).

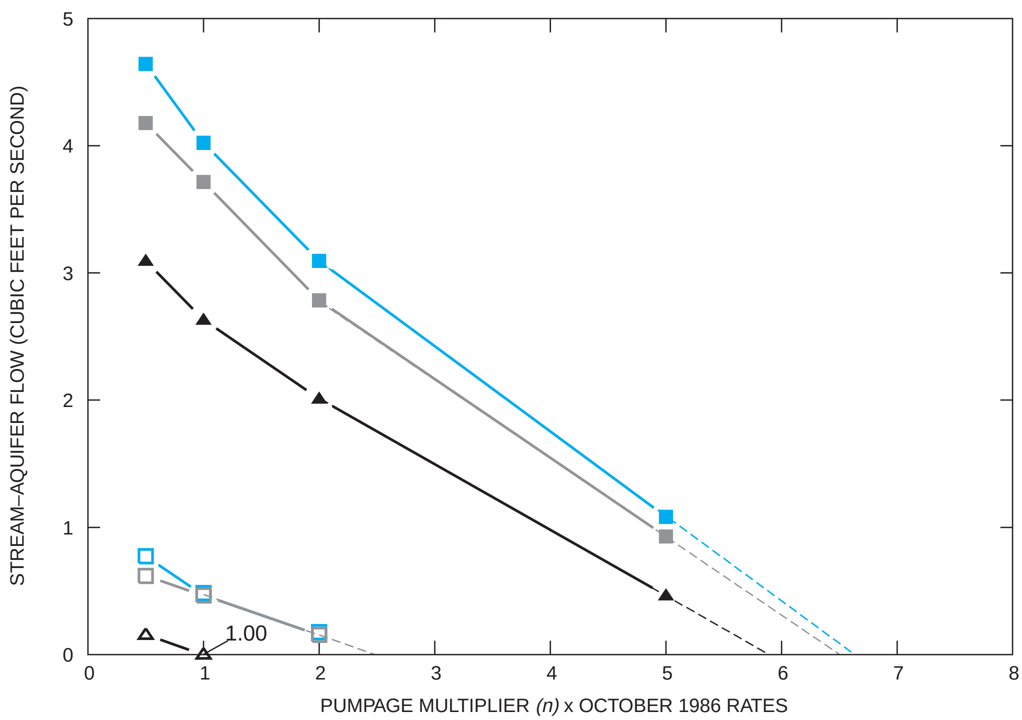

Figure B7. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 7, Cooleewahee Creek, Georgia (see fig. 8 for location).

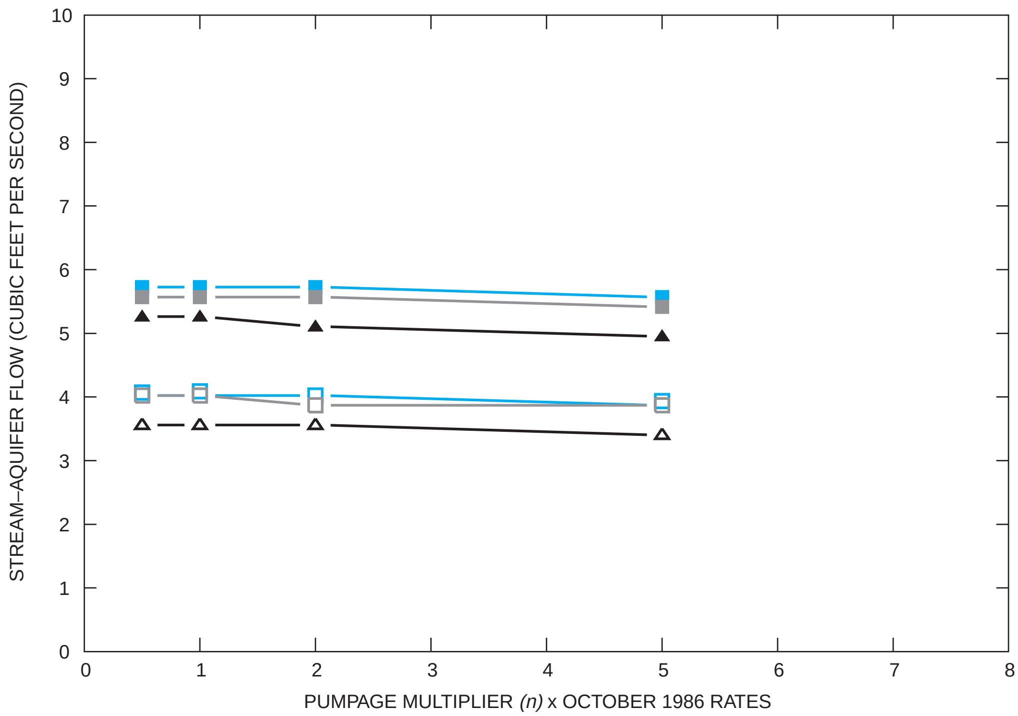

Figure B8. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 8, Chickasawhatchee Creek, Georgia (see fig. 8 for location).

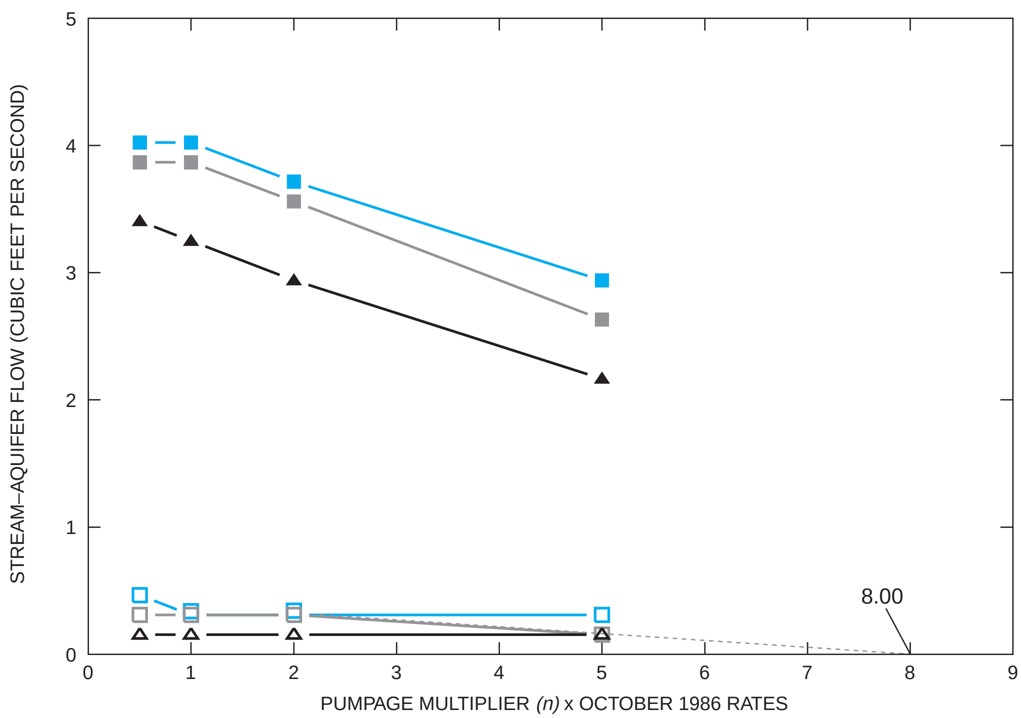

Figure B9. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 9, Chickasawhatchee Creek, Georgia (see fig. 8 for location).

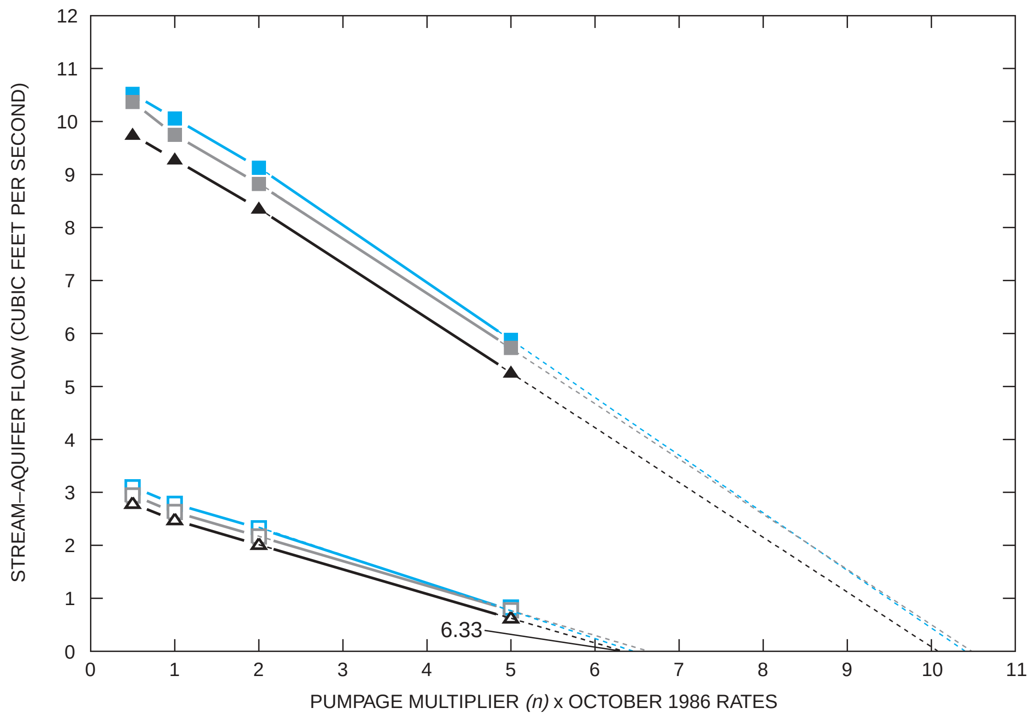

Figure B10. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 10, Chickasawhatchee Creek, Georgia (see fig. 8 for location).

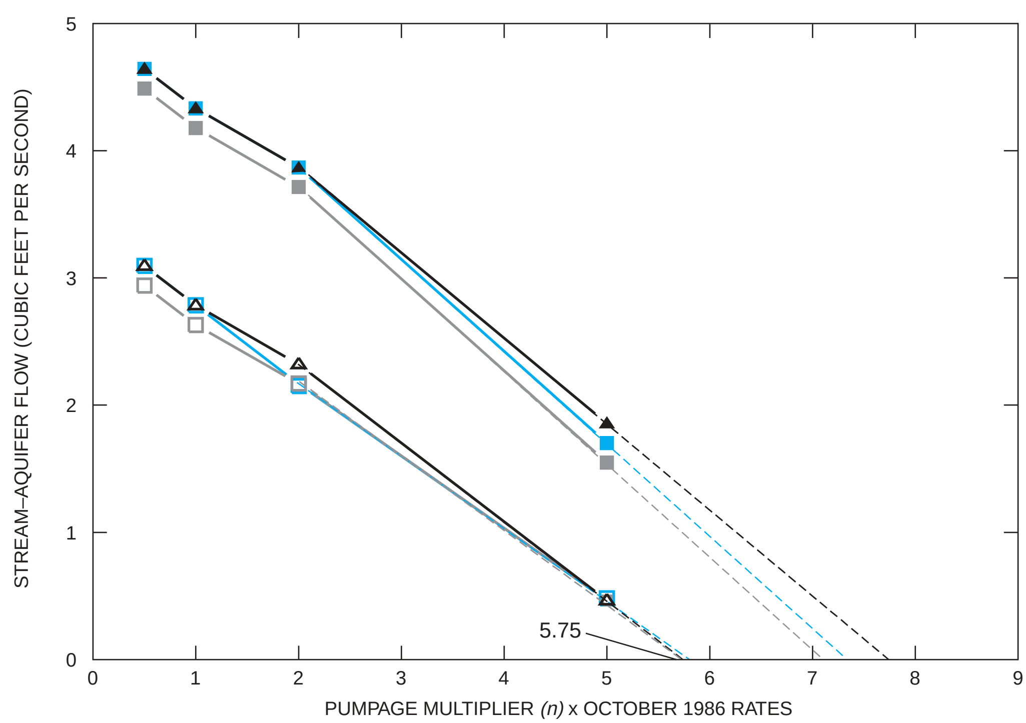

Figure B11. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 11, Dry Creek, Georgia (see fig. 8 for location).

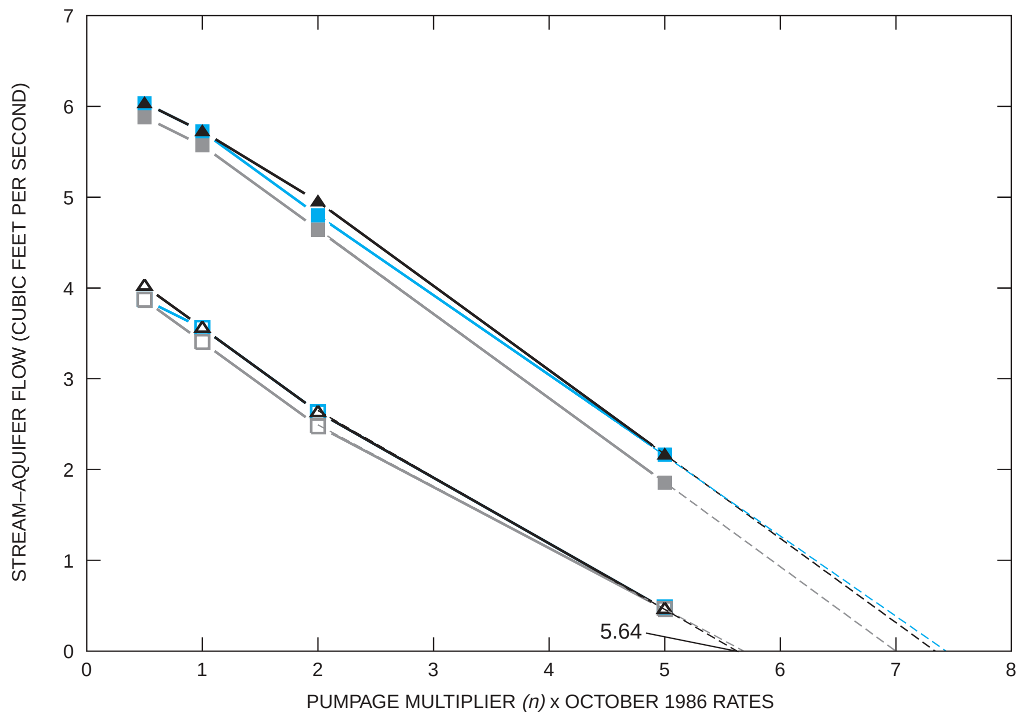

Figure B12. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 12, Spring Creek, Georgia (see fig. 8 for location).

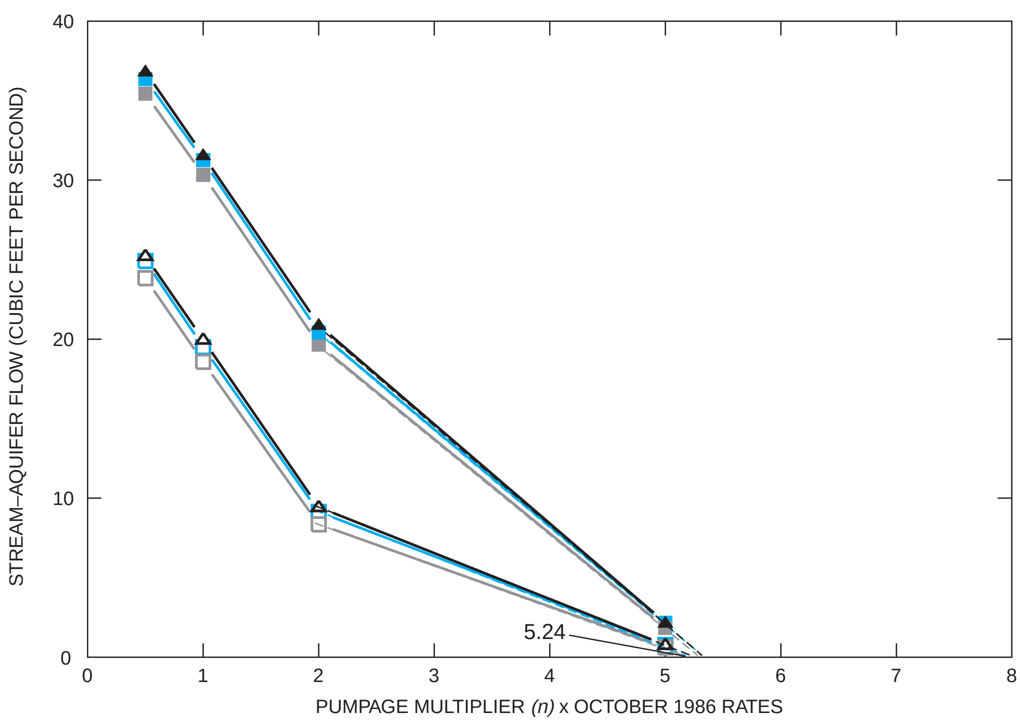

Figure B13. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 13, Spring Creek, Georgia (see fig. 8 for location).

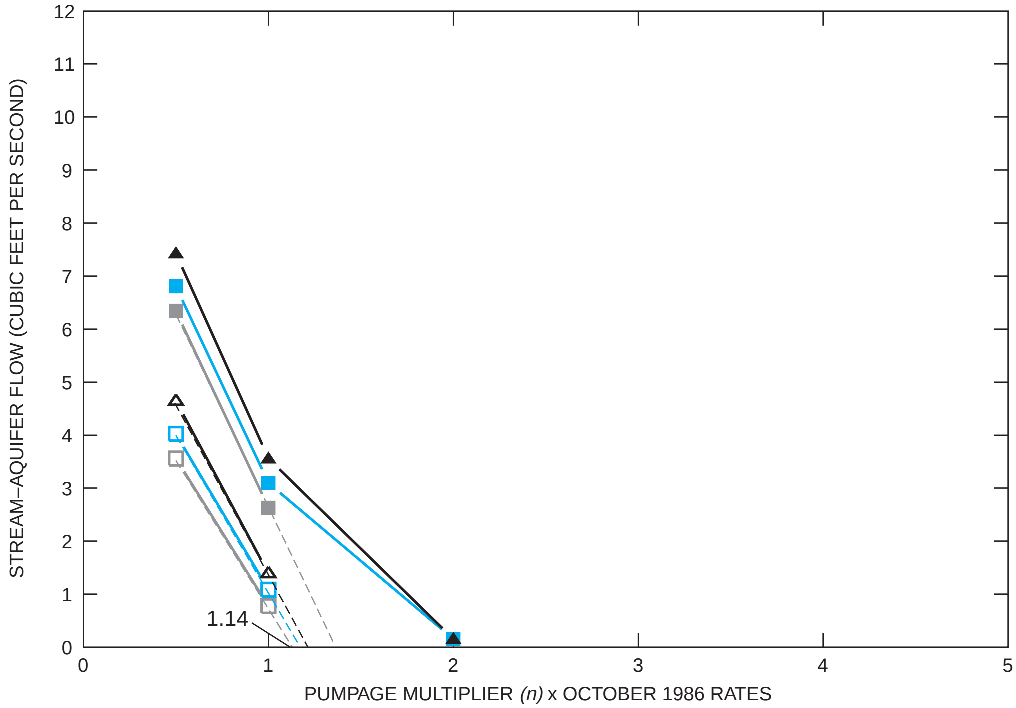

Figure B14. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 14, Spring Creek, Georgia (see fig. 8 for location).

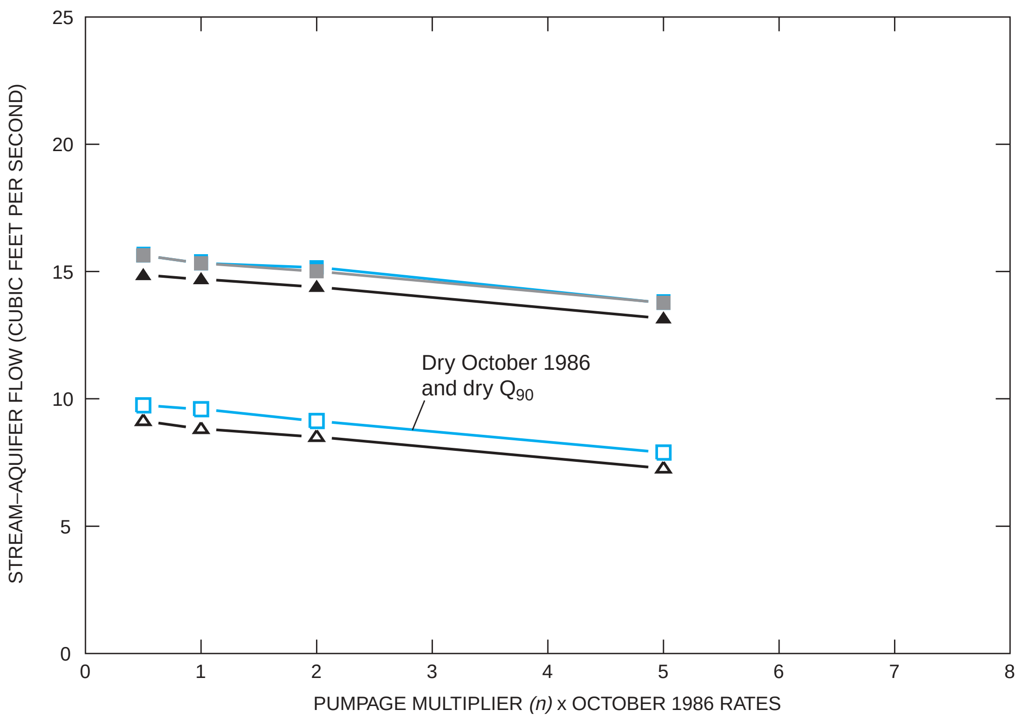

Figure B15. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 15, Sawhatchee Creek, Georgia (see fig. 8 for location).

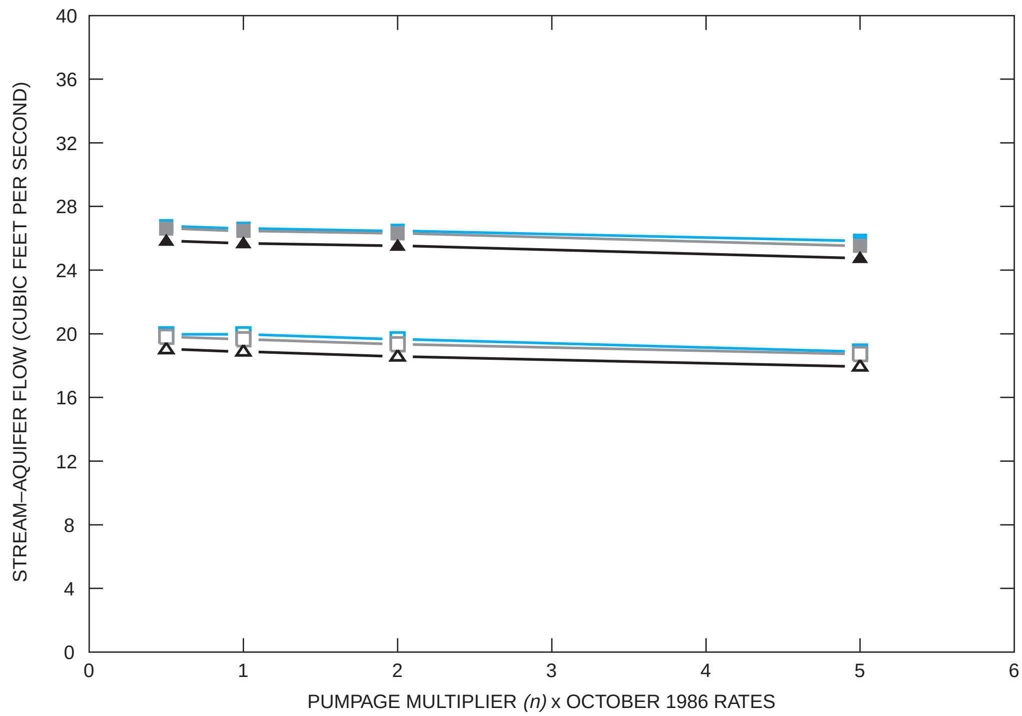

Figure B16. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 16, Cowarts Creek, Florida (see fig. 8 for location).

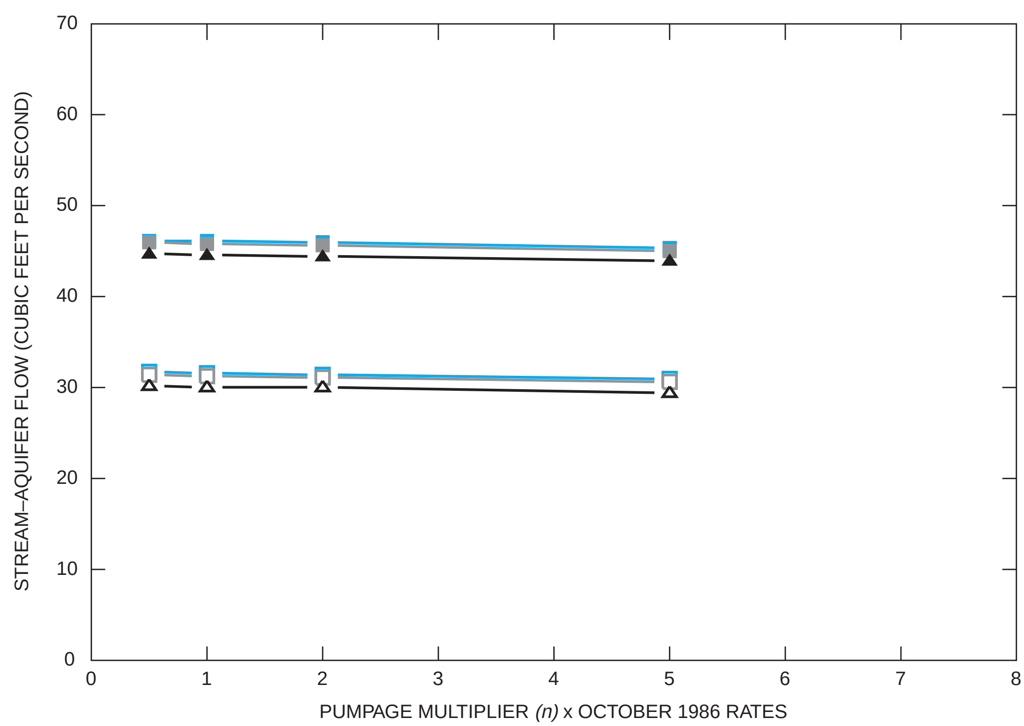

Figure B17. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach17, Marshall Creek, Florida (see fig. 8 for location).

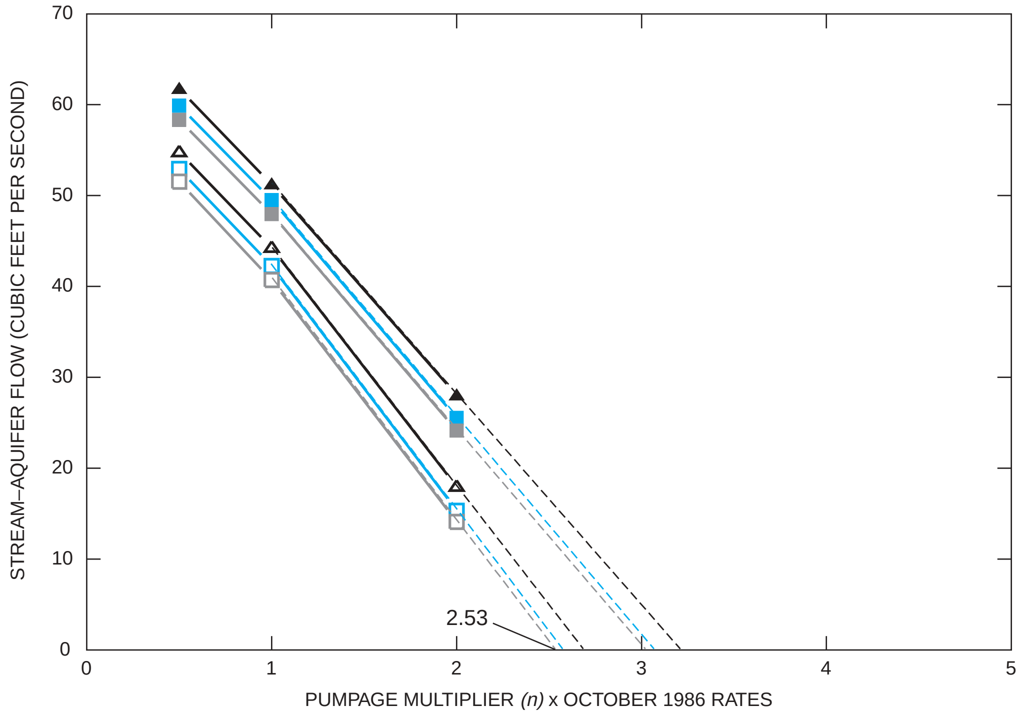

Figure B18. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 18, Spring Creek, Georgia (see fig. 8 for location).

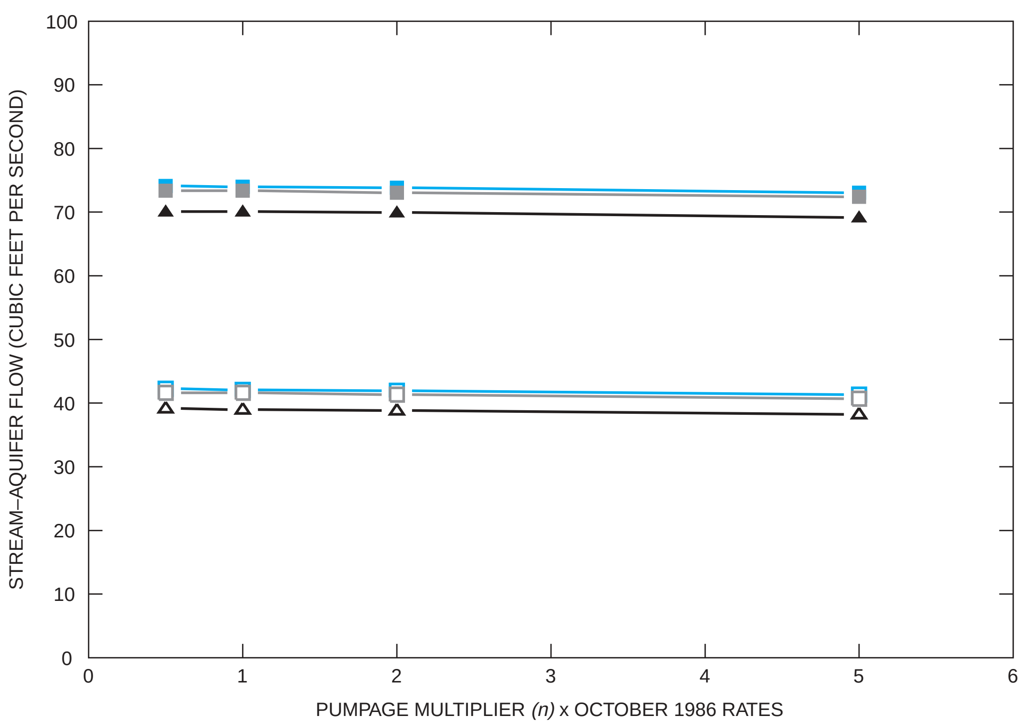

Figure B19. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 19, Dry Creek, Florida (see fig. 8 for location).

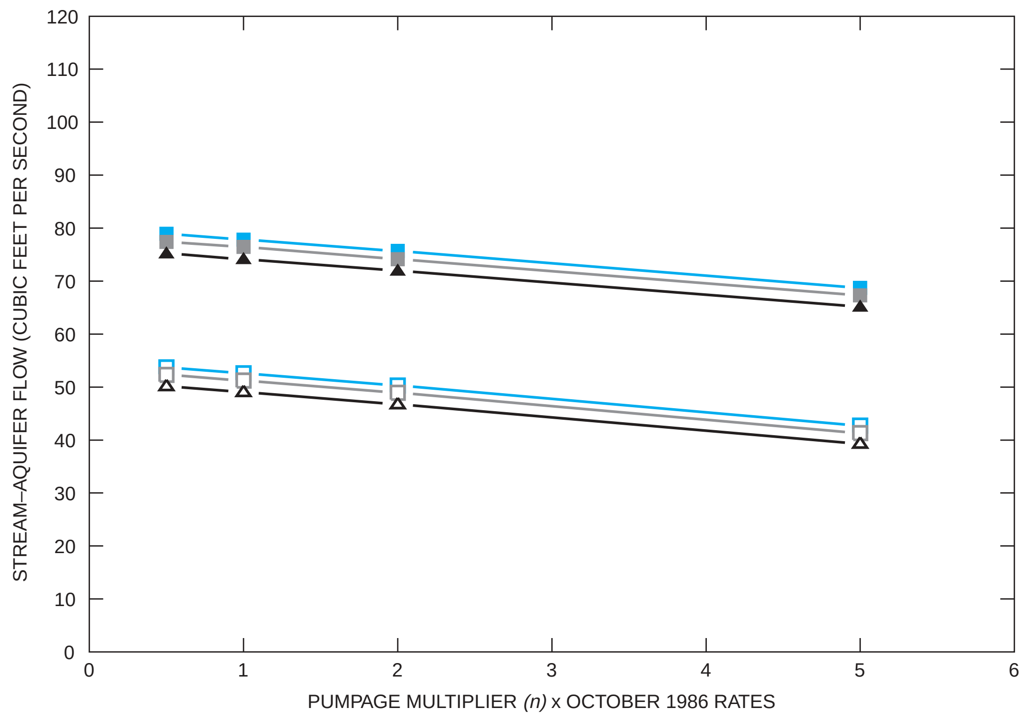

Figure B20. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 20, Ichawaynochaway Creek, Georgia (see fig. 8 for location).

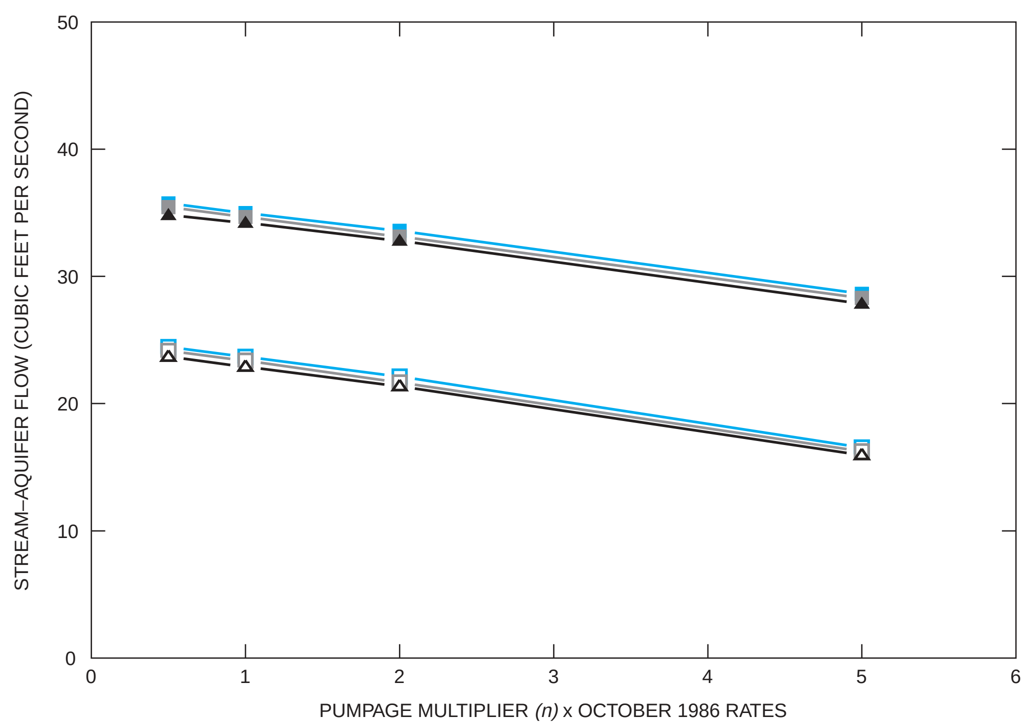

Figure B21. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 21, Ichawaynochaway Creek, Georgia (see fig. 8 for location).

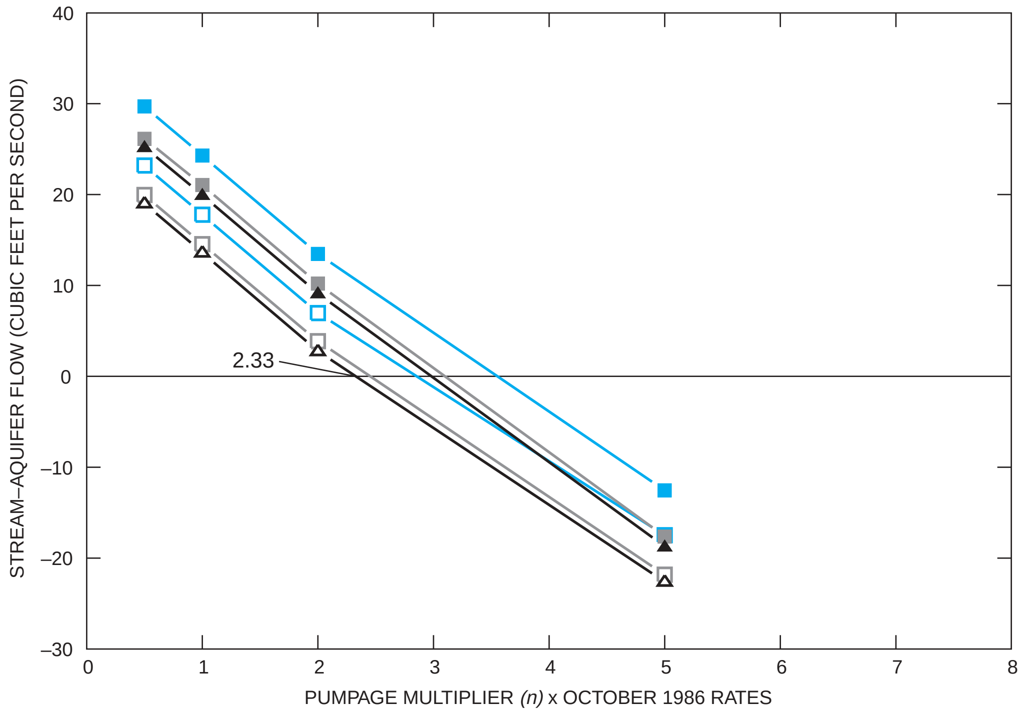

Figure B22. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 22, Muckalee Creek, Georgia (see fig. 8 for location).

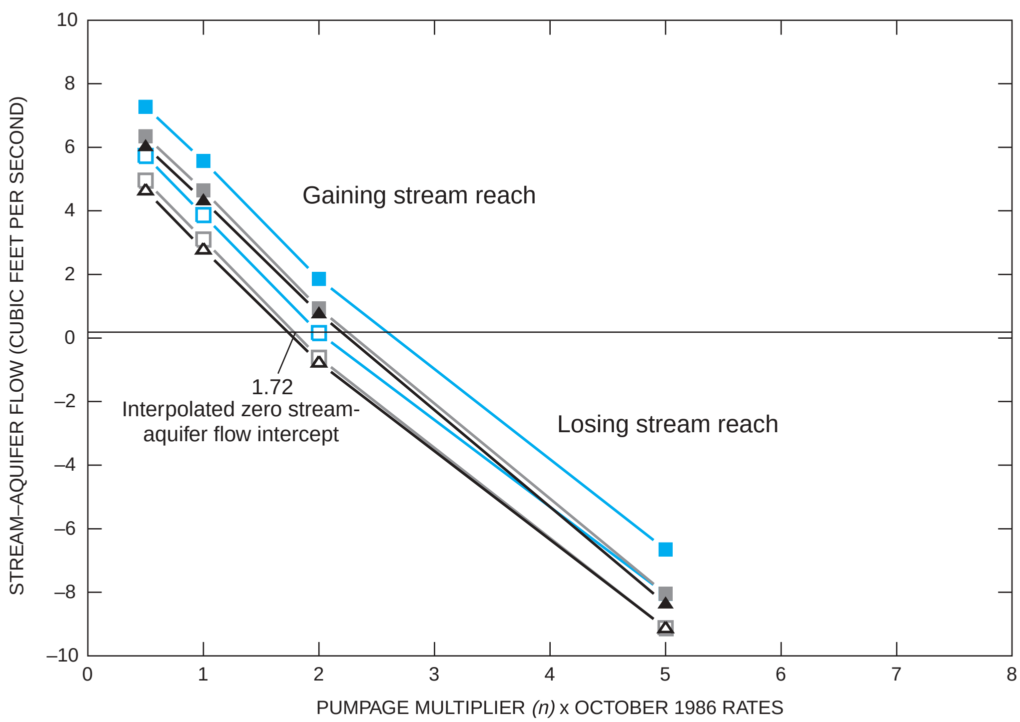

Figure B23. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 23, Muckalee Creek, Georgia (see fig. 8 for location).

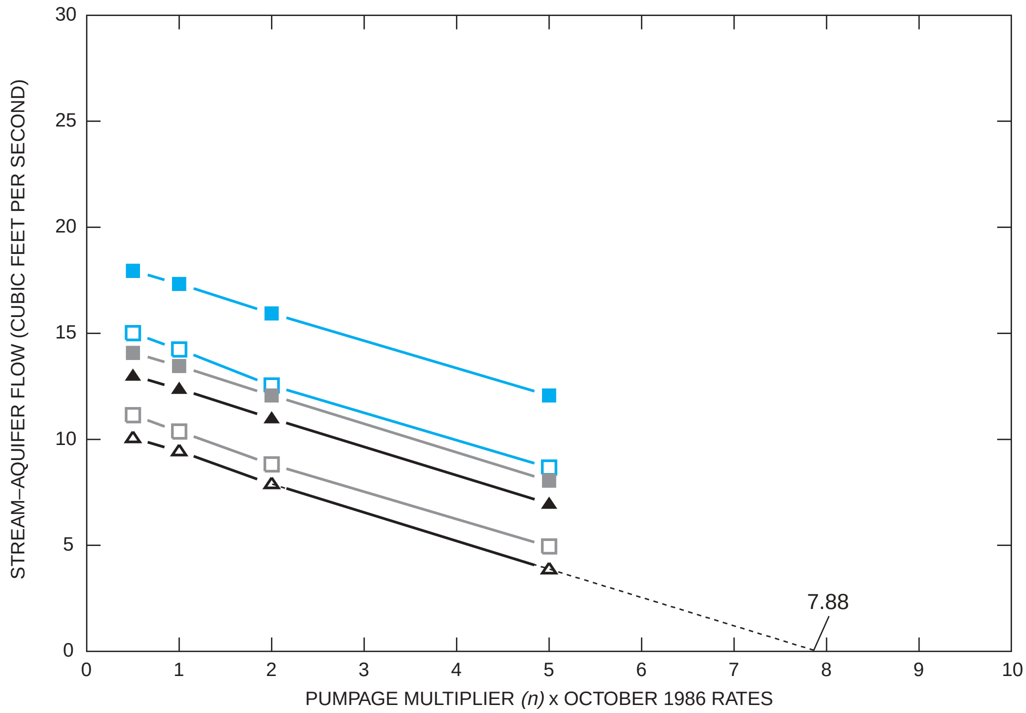

Figure B24. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 24, Muckalee Creek, Georgia (see fig. 8 for location).

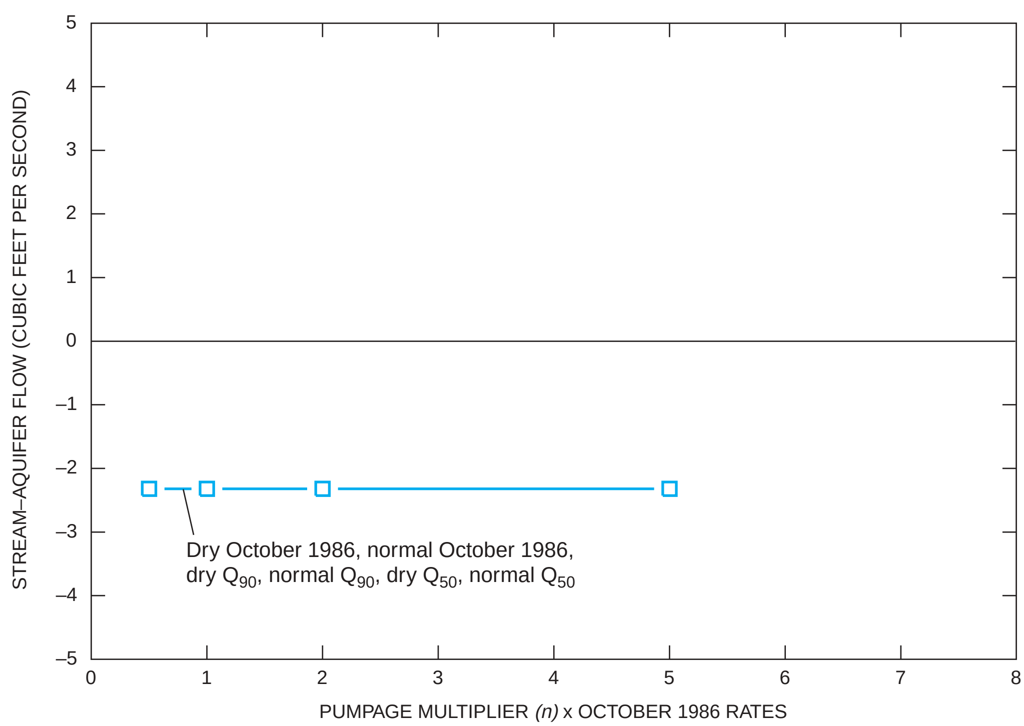

Figure B25. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 25, Kinchafoonee Creek, Georgia (see fig. 8 for location).

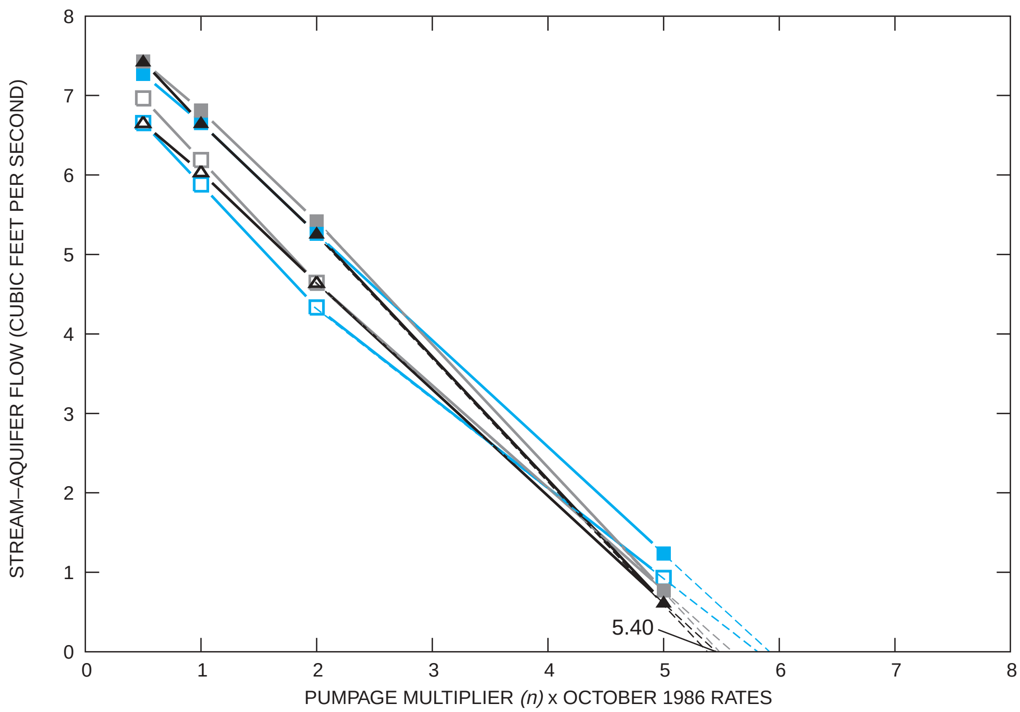

Figure B26. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 26, Kinchafoonee Creek, Georgia (see fig. 8 for location).

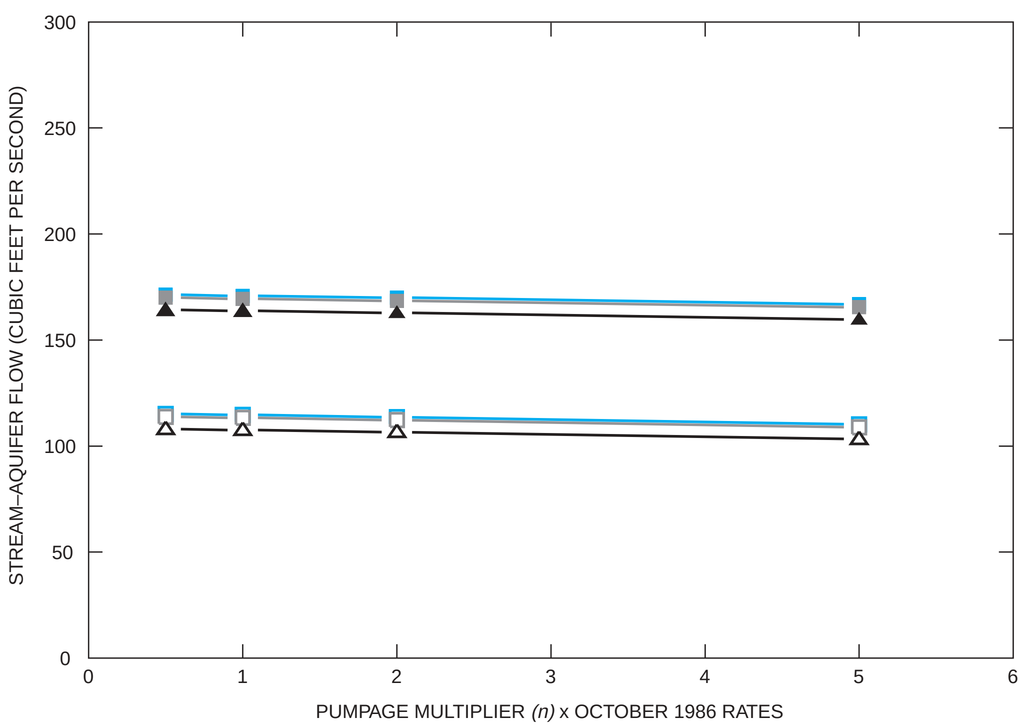

Figure B27. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 27, Chipola River, Florida (see fig. 8 for location).

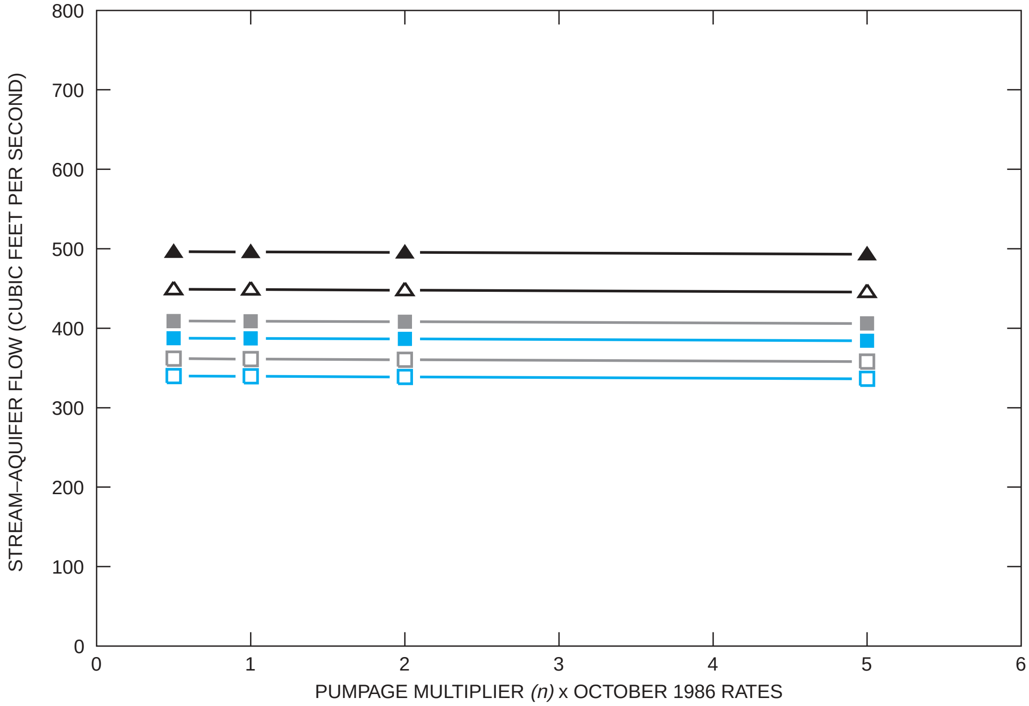

Figure B28. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 28, Chipola River, Florida (see fig. 8 for location).

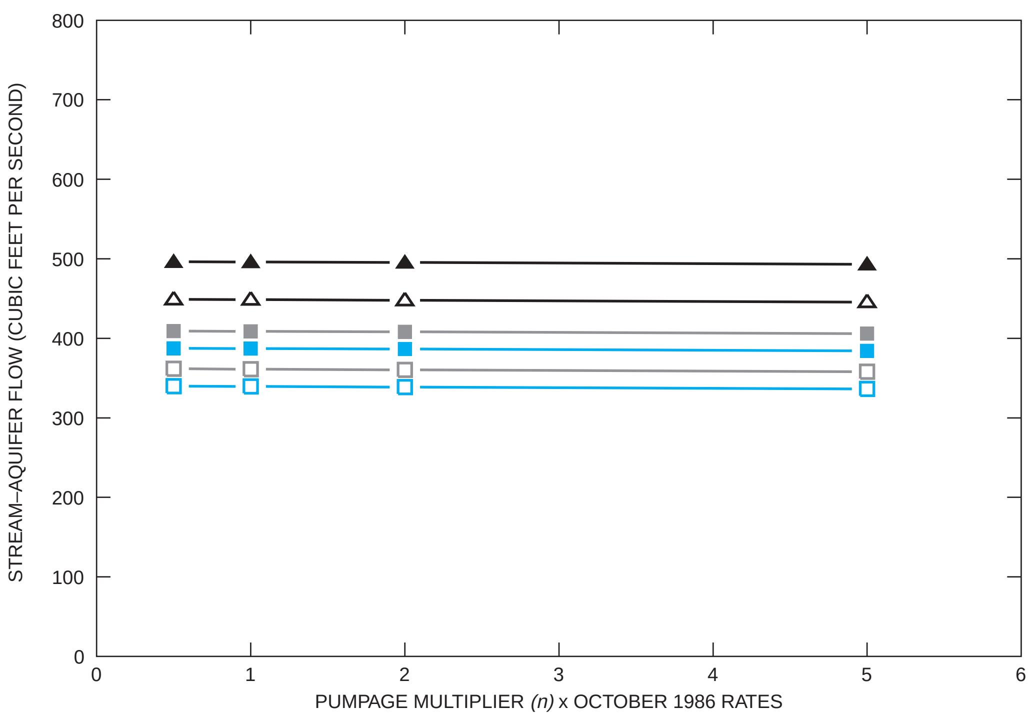

Figure B29. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 29, Chipola River, Florida (see fig. 8 for location).

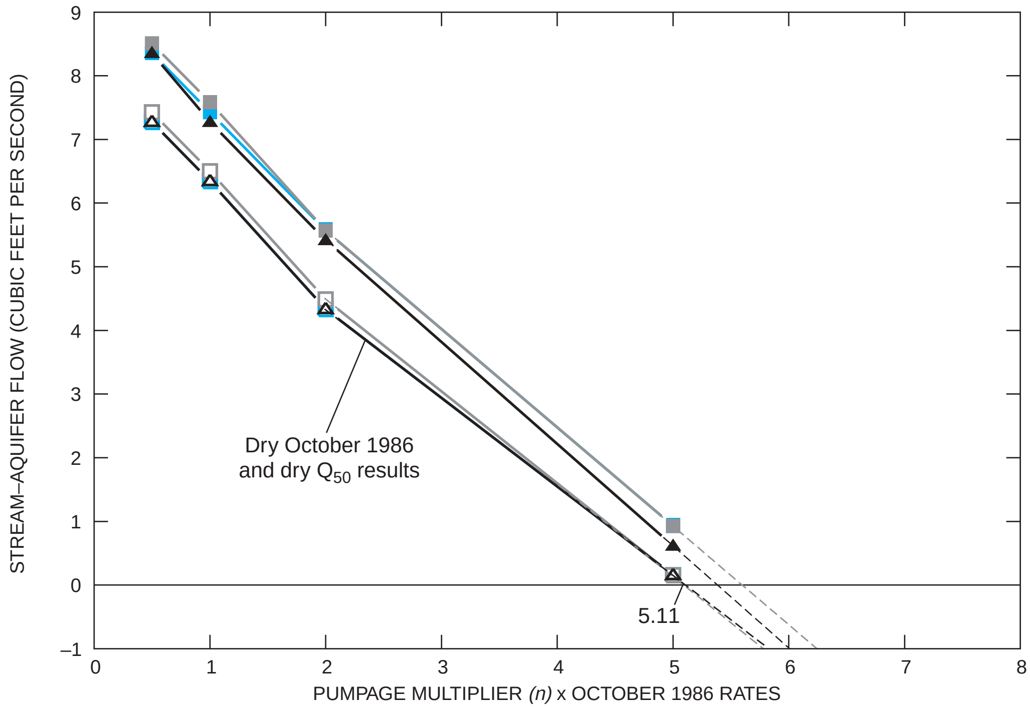

Figure B30. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 30, Flint River, Georgia (see fig. 8 for location).

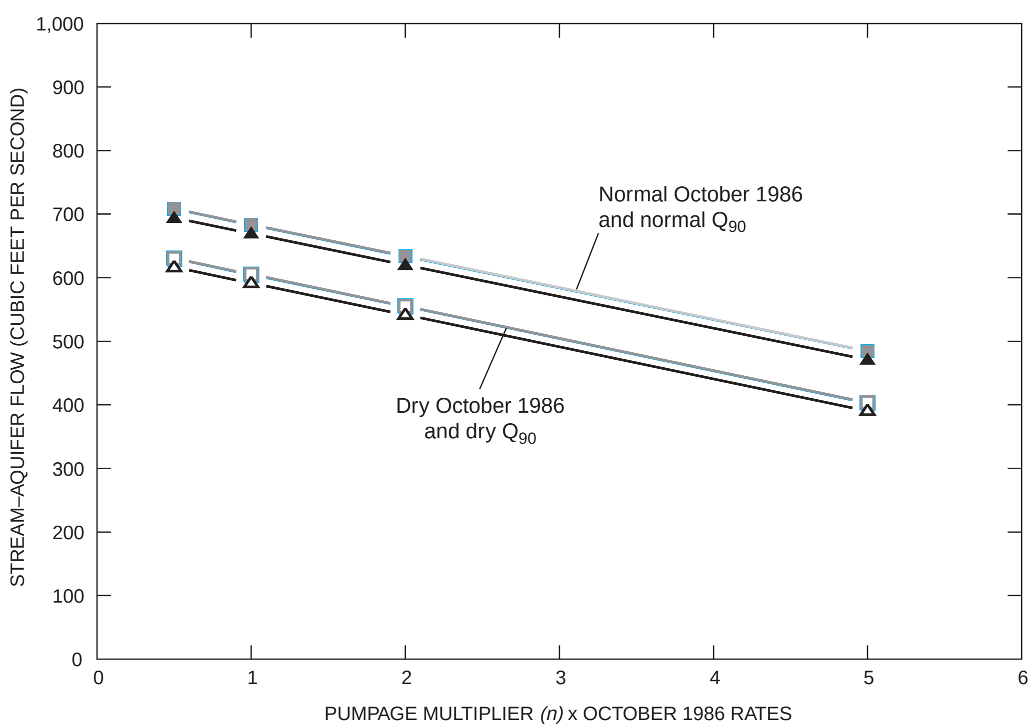

Figure B31. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 31, Flint River, Georgia (see fig. 8 for location).

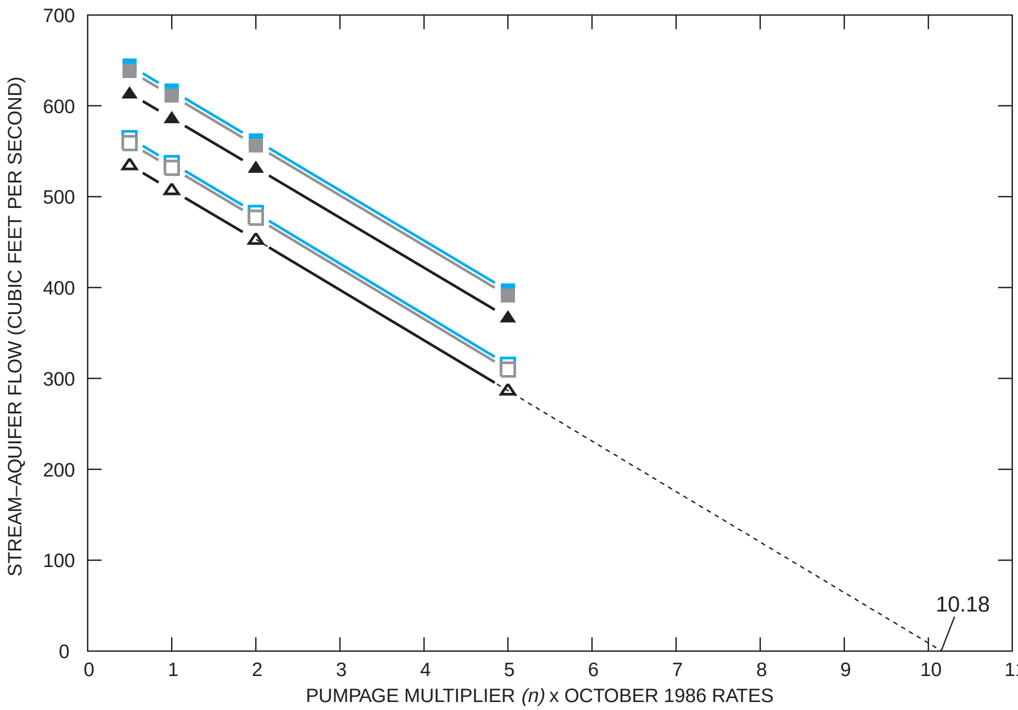

Figure B32. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 32, Flint River, Georgia (see fig. 8 for location).

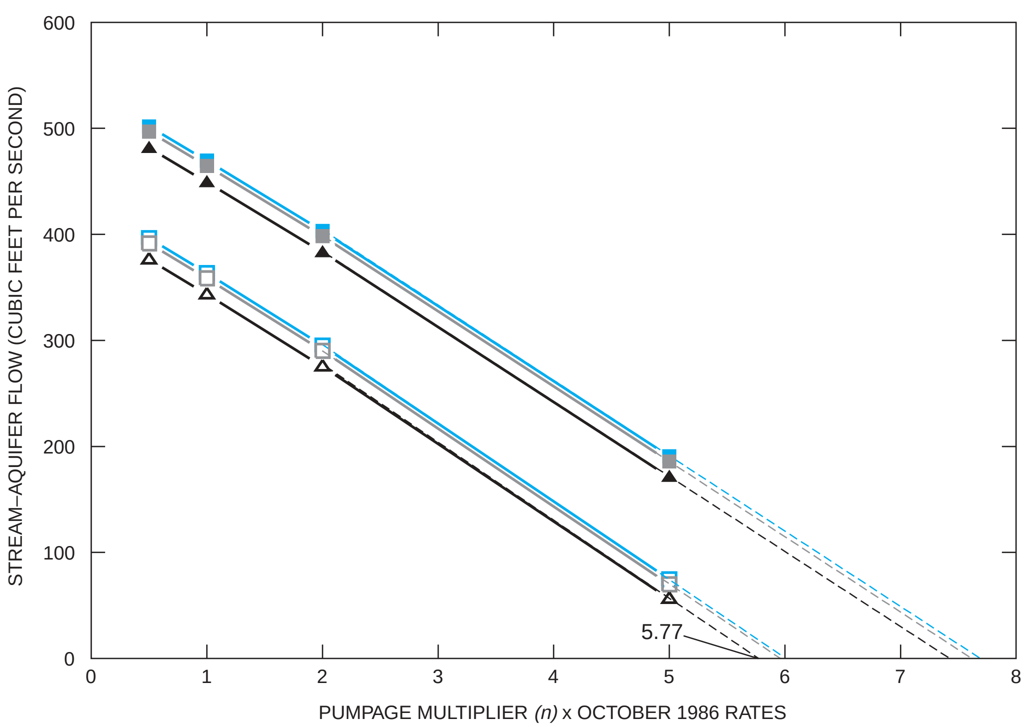

Figure B33. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 33, Flint River, Georgia (see fig. 8 for location).

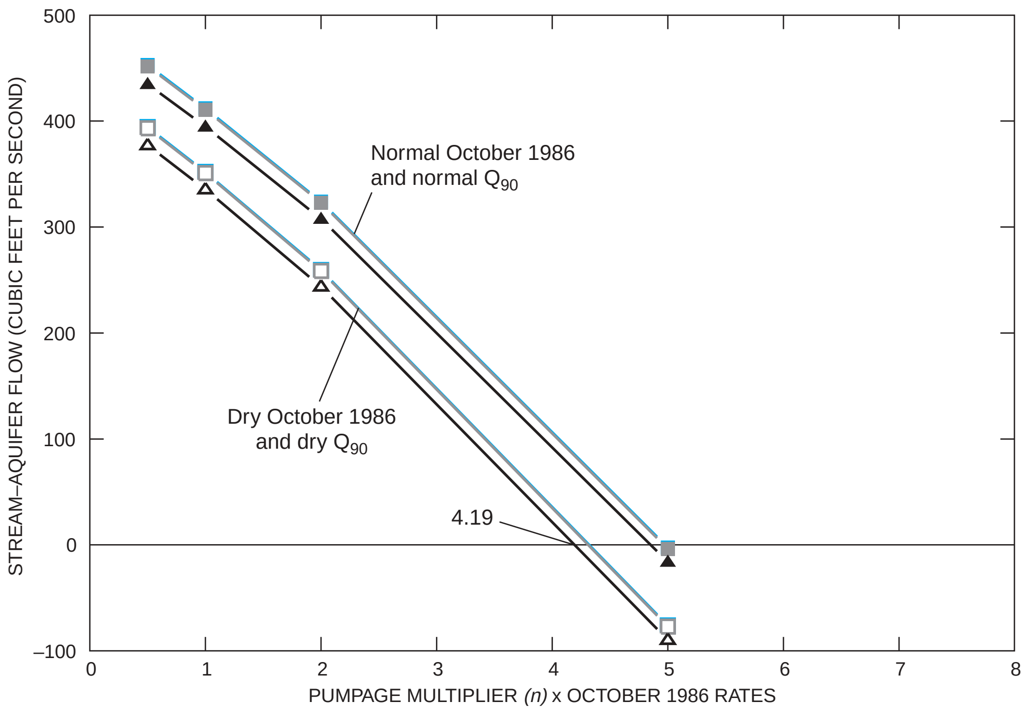

Figure B34. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 34, Flint River, Georgia (see fig. 8 for location).

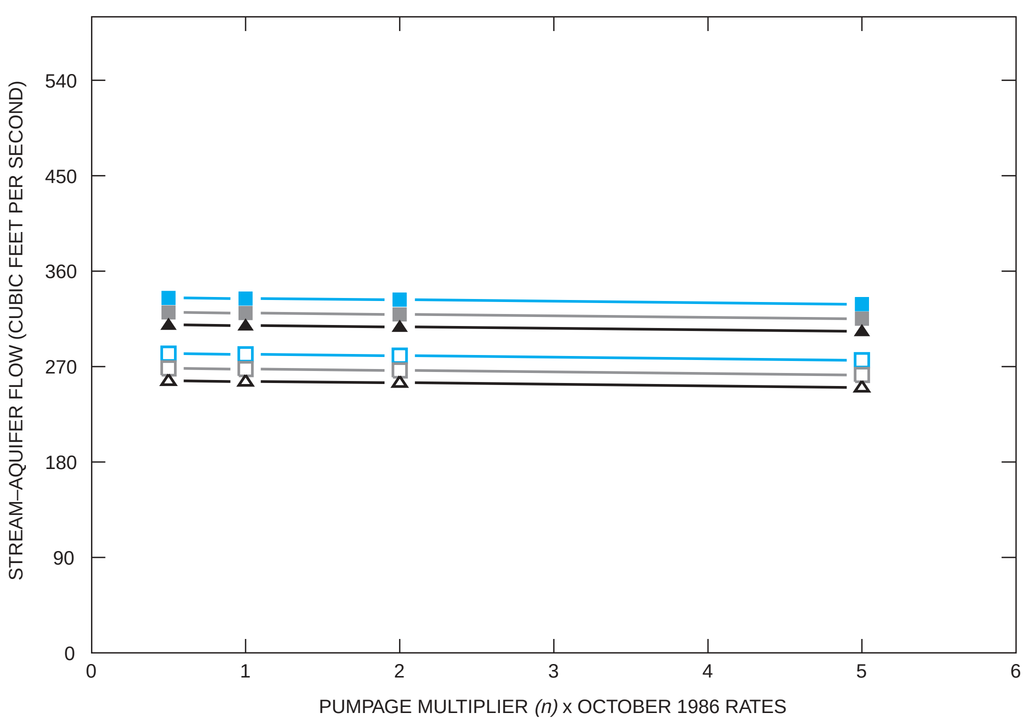

Figure B35. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 35, Apalachicola River, Florida (see fig. 8 for location).

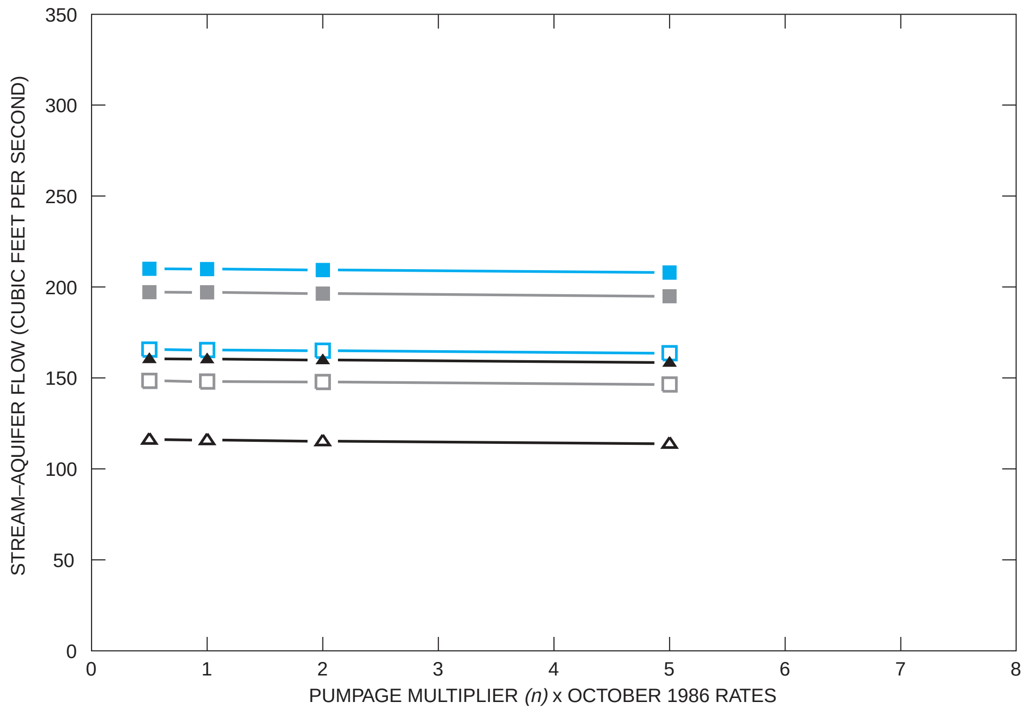

Figure B36 Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 36, Apalachicola River, Florida (see fig. 8 for location).

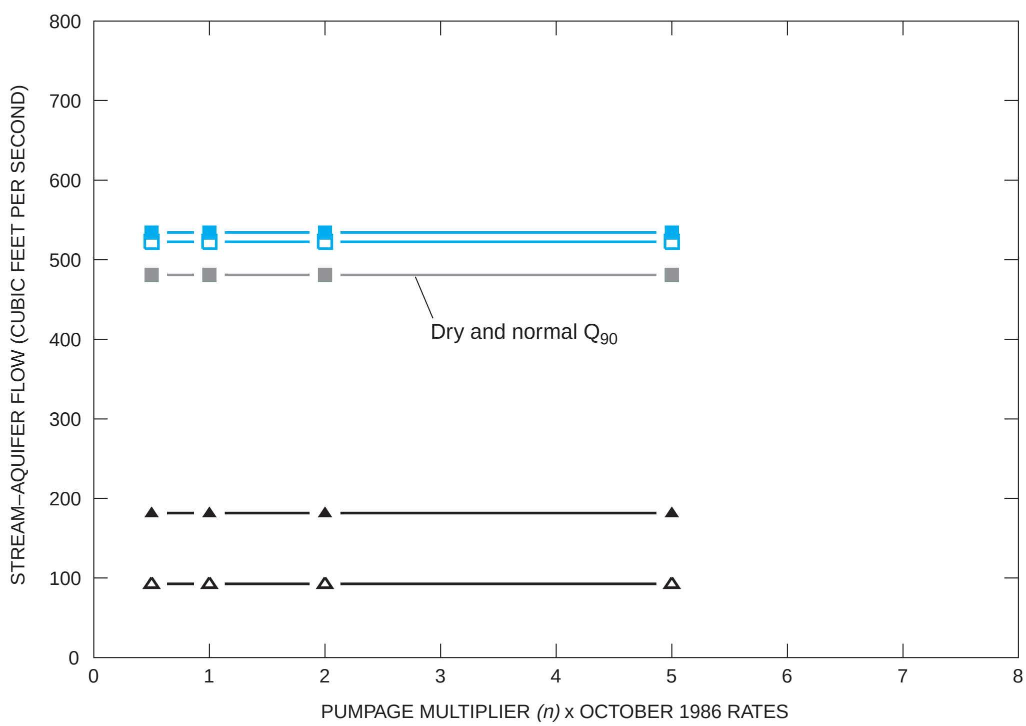

Figure B37. Stream-aquifer flow for simulated pumpage scenarios, ground-water boundary conditions, and stream stage at October 1986, Q_{90}, and Q_{50} levels for reach 37, Apalachicola River, Florida (see fig. 8 for location).